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LABORATORY EVALUATION OF SELECTED TAR SAND ASPHALTS

By
Joe W. Button
Jon A. Epps
Bob M. Gallaway

December 1980

Work Performed Under Contract No. DE-AC20-78LC10049

Transportation Institute
Texas A&M University
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TECHNICAL INFORMATION CENTER
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Laboratory Evaluation

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ABSTRACT

Three tar sand asphalts of similar grades prepared from one syncrude by three different refining methods were characterized by tests commonly used to specify paving asphalts together with certain special tests. Asphalt-aggregate mixtures were prepared using these asphalts and tested in the laboratory to determine strength stiffness stability, tensile properties, temperature effects and water susceptibility. Comparison of the tar sand asphalt properties to conventional petroleum asphalt properties reveal no striking differences.

INTRODUCTION

The research described herein is Phase II of a study of asphalts obtained from, as yet, untapped domestic fossil fuel resources. Phase I involved characterization of shale oil asphalts prepared from shale oil from the Green River formation in Colorado (1). Phase II involved a similar characterization of tar sand asphalts obtained from the in situ retorting of tar sand bitumen in the TS-2C burn (2) conducted near Vernal, Utah, by the Laramie Energy Technology Center of the U. S. Department of Energy on property made available by Sohio Natural Resource Company.

By definition, a tar sand or oil sand is a sedimentary rock (consolidated or unconsolidated) that contains bitumen (solid or semisolid hydrocarbons) or other heavy petroleums that, in natural state, cannot be recovered by conventional petroleum-recovery methods (3). Tar sand is one of the greatest energy resources on earth. Canada has the largest deposit which is considered to be the largest single deposit of liquid petroleum in the world (4). The states of Utah, California, Kentucky, New Mexico and Missouri have oil sand deposits with in-place oil volumes estimated to total more than 25 billion barrels (4.0×10^9 m^3). Recoverable reserves for the U. S. tar sands are placed at 2.5 to 5.5 billion barrels (4.0 to 8.7×10^4 m^3). The best known oil sand deposits of the United States occur within and around the periphery of the Unita Basin in Utah (5) (6) (see Appendix E).

Since seventy-five percent of the asphalt produced in the United States is utilized by the paving industry, it is essential to determine whether or not asphalt from new sources is suitable for paving applications. For this reason the U. S. Department of Energy sponsored this research study at Texas A&M University.

The objective of this study was to determine the suitability of tar sand asphalts for paving purposes. Selected tar sand asphalt cements were characterized by tests commonly utilized to specify paving asphalts together with certain special tests. Asphalt-aggregate mixtures were fabricated from these asphalts and subjected to tests used in specifying paving mixtures. Data from these tests were compared with the characteristics of petroleum asphalts and petroleum asphalt mixtures.

Based on the laboratory test results, the tar sand asphalts exhibited rather high temperature susceptibility in the higher temperature range (mixing and compaction) but low temperature susceptibility in the lower temperature range (pavement performance). After the thin film oven test, ductility was comparatively low and loss on heating exceeded the specified limit. One tar sand asphalt, manufactured using a solvent separation process exhibited excessive hardening upon heating. Two tar sand asphalts produced by different distillation processes yielded paving mixtures that displayed little damage by water, whereas, the tar sand asphalt manufactured by the solvent process was more water susceptible. Generally, properties of the asphalt-aggregate mixtures were shown to be satisfactory when compared to standard specifications.

ASPHALT CEMENT PROPERTIES

General

Three asphalt cements comparable in viscosity to a conventional AC-10 were produced by three different simulated refining methods from a common sample of tar sand oil. The tar sand asphalts prepared from TS-2C in situ oil were supplied by the Department of Energy's Laramie Energy Technology Center in Laramie, Wyoming. The three simulated refining processes utilized were vacuum distillation, flash vaporization, and selective solvent extraction. This affords a unique opportunity not only to observe the properties of asphalts from tar sand but also to compare differences in asphalts produced from the same crude by different methods. Because of the constraints in the scope of the study, processing conditions and resulting product properties were not optimized.

Vacuum distillation of the tar sand oil employed a bottoms temperature of just over 720°F (corrected to 760 mm Hg). Flash vaporization was conducted at 730°F (corrected to 760 mm Hg) and 5 mm Hg. Vacuum distillation and flash vaporization were performed by Gulf Research and Development Company. Solvent extraction was accomplished by Kerr-McGee using their ROSE process which involves high pressure and an aliphatic solvent. The laboratory standard material or control was an AC-10 petroleum asphalt cement produced by vacuum distillation in 1976 by the American Petrofina Company at Mt. Pleasant, Texas.

These asphalts will be referred to throughout this report in accordance with the following code:

Production Method	Asphalt Code
Vacuum Distillation	D
Flash Vaporization	F
Solvent Extraction (ROSE)	R
Laboratory Standard	LS

Discussion of Test Results

Standarized Tests were conducted to determine the basic asphalt characteristics. Certain special tests were performed to predict the in-service durability of tar sand asphalts. The types of tests performed and the results are presented in Table 1. Consistency of the original asphalts are described by penetration, viscosity and softening point. These values have been plotted on the Bitumen Test Data Chart (7) to illustrate their interrelationships (Figures 1 through 4). Viscosity data has been plotted on the ASTM D 2493 viscosity-temperature chart (Figure 5).

The tar sand asphalts exhibit comparatively low viscosities and/or high penetrations at 77°F (25°C). This results in low values of

Table 1. Original Asphalt Cement Properties.

Asphalt Code	D	F	R	LS
Production Method	Vacuum Dist.	Flash Vap.	Solvent Process	Vacuum Dist.
Viscosity, 77°F (25°C) poise	2.6×10^5	2.3×10^5	3.6×10^5	5.8×10^5
Viscosity, 140°F (60°C) poise	1070	960	1100	1580
Viscosity, 275°F (135°C) poise	1.36	1.29	1.82	3.8
Penetration, 77°F (25°C), dmm (100 gm, @ 5 sec)	196	208	172	118
Penetration, 60°F (16°C), dmm (100 gm @ 5 sec)	55	67	70	--
Penetration, 39.2°F (4°C) dmm (100 gm @ 5 sec)	14	12	13	4
Penetration, 39.2°F (4°C) dmm (200 gm @ 60 sec)	55	65	68	26
Soft Point, R & B, °F (°C)	127 (53)	121 (50)	112 (45)	107 (42)
Specific Gravity, 77°F (25°C)	.998	.995	.998	1.02
Ductility, 77°F (25°C) cm	53	60	83	150+
Solub., (CH Cl:CCL_2), %	94	95	96	99.99
Spot Test	Pos.	Pos	Pos.	Pos.
Flash Point, °F (°C)	544 (285)	499 (260)	454 (235)	615 (324)
Fire Point, °F (°C)	568 (298)	562 (295)	490 (255)	697 (370)
Thin Film Oven Test				
Pen. of Residue, 77°F	88	94	34	68
Duct. of Residue, 77°F	62	101	53	150+
Vis. of Residue, 140°F	3400	3800	11,800	3050
Loss on Heating, percent	1.5	2.1	6.0	Neg.
Hardening Index (due to actinic light)	1.7	1.8	5.8	1.9
Vanadium Content, ppm (deashed asphalt)	3.8	--	4.3	3.4

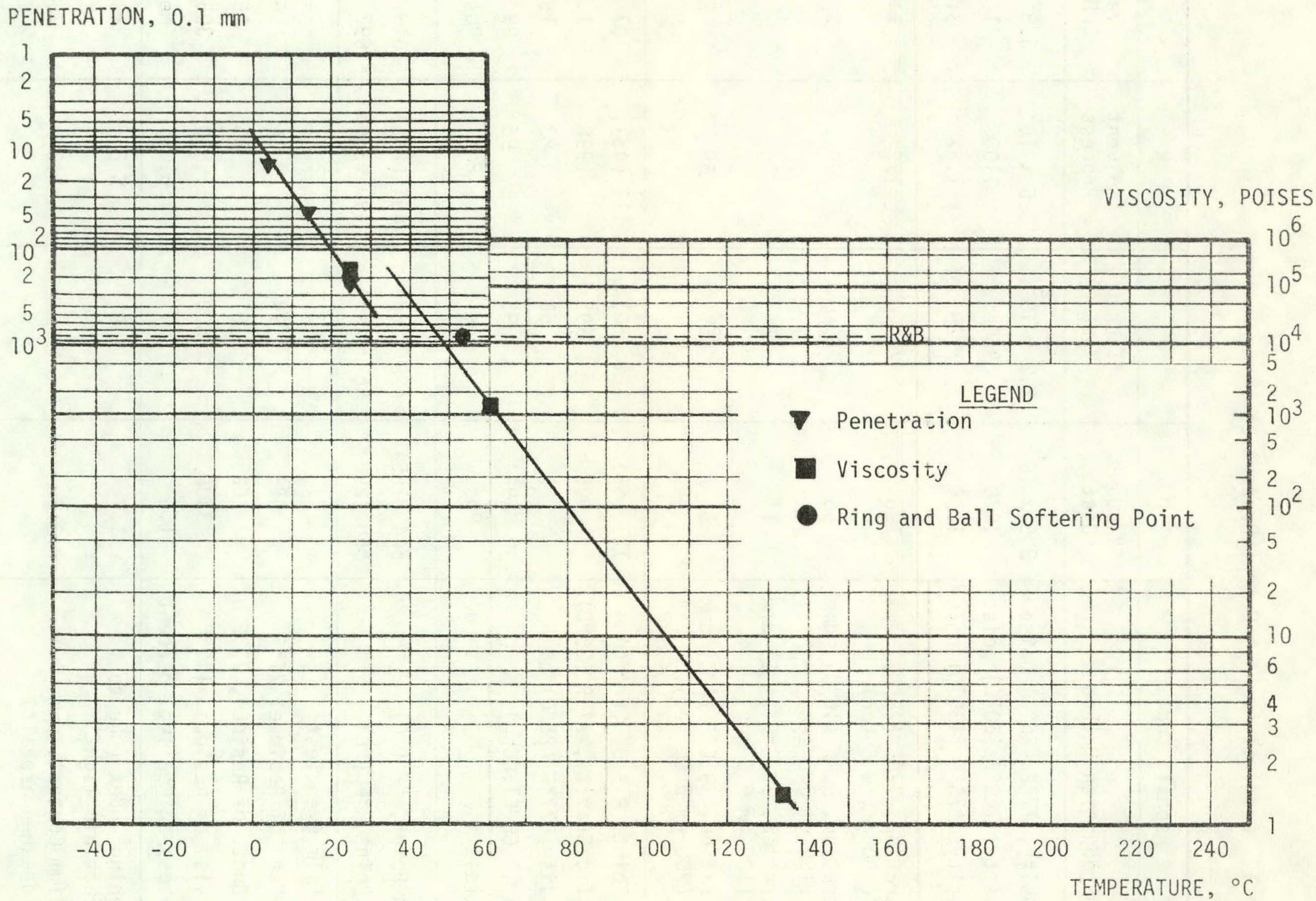

Figure 1. Bitumen Test Data Chart Showing Properties of Asphalt D.

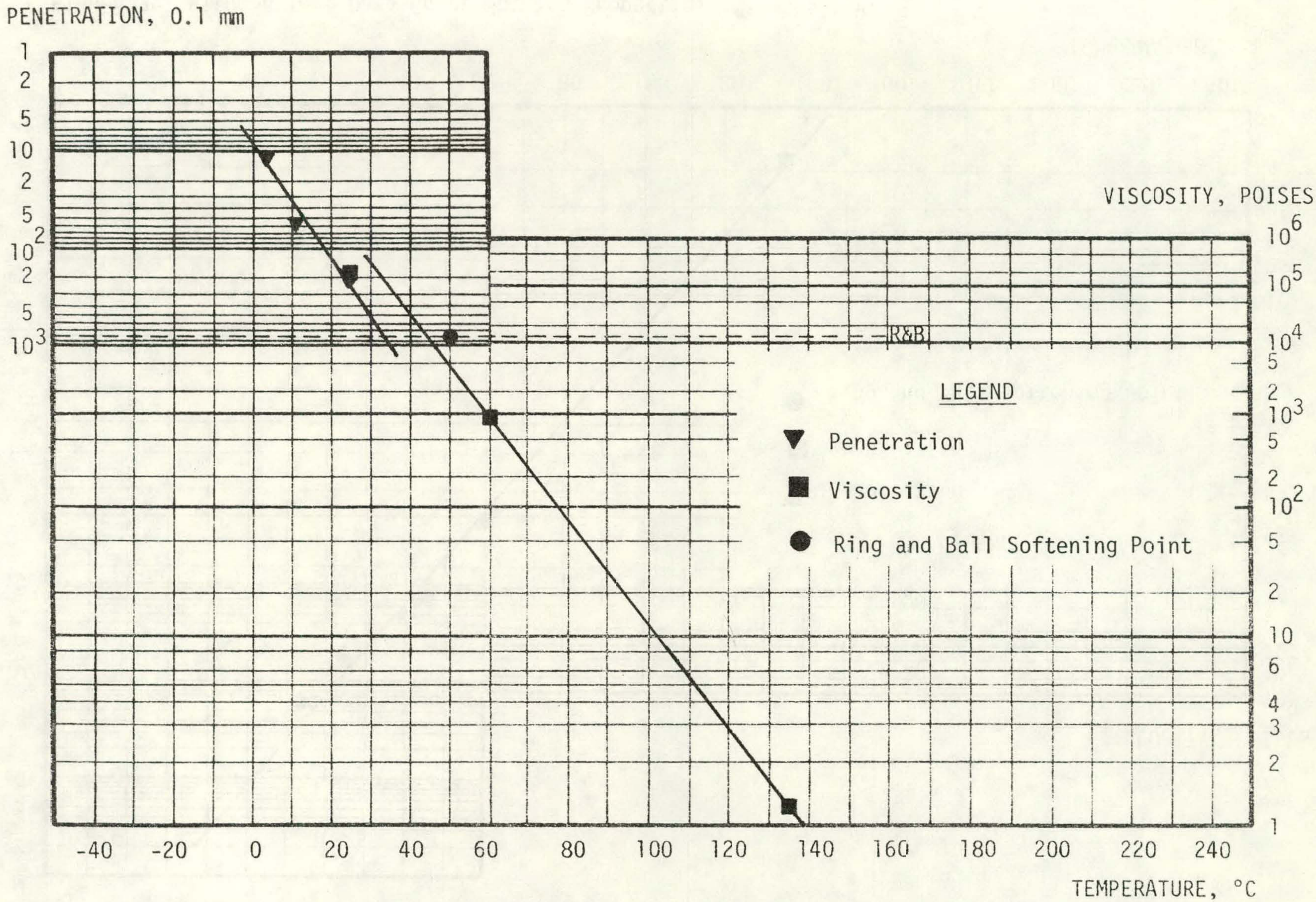

Figure 2. Bitumen Test Data Chart Showing Properties of Asphalt F.

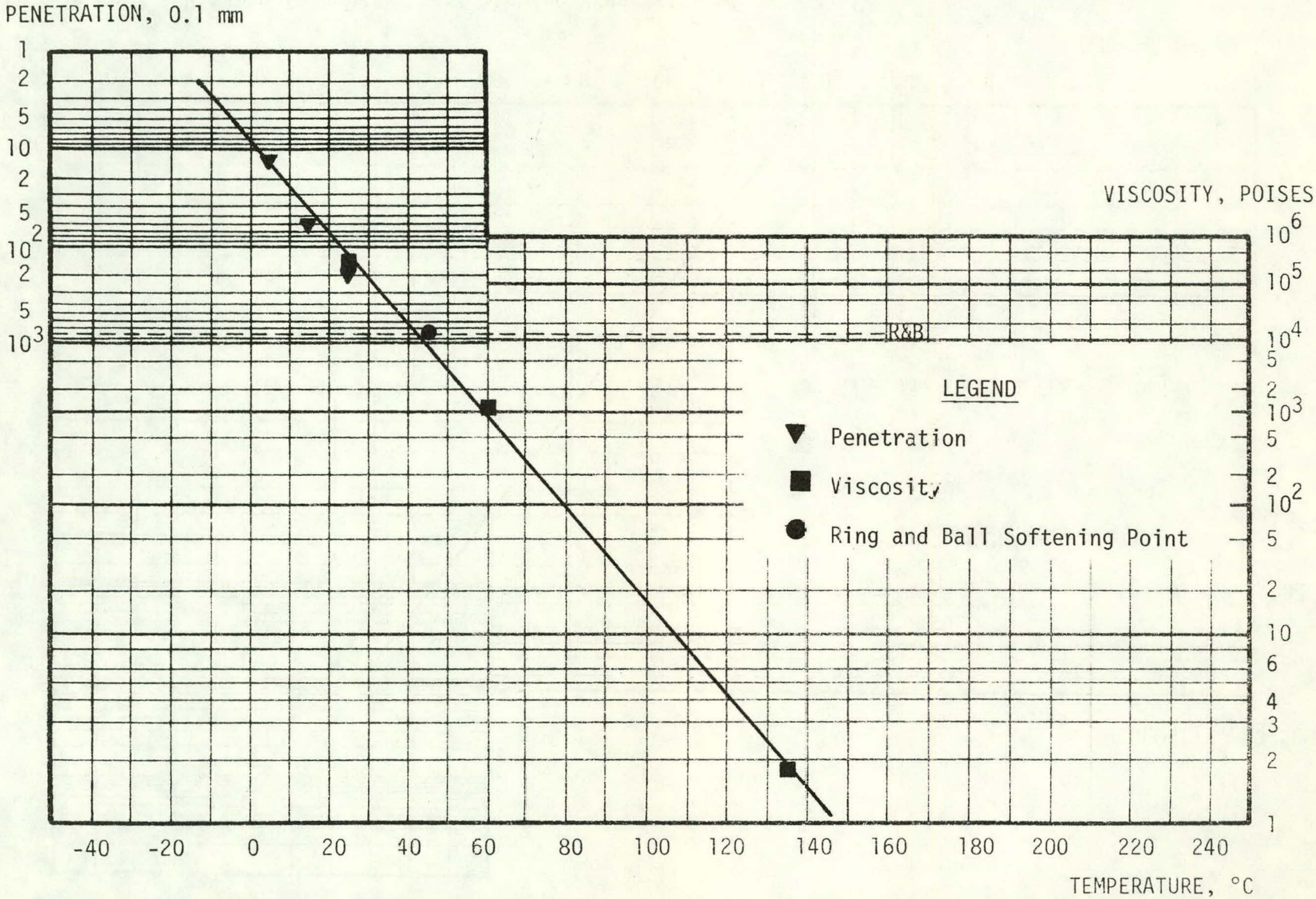

Figure 3. Bitumen Test Data Chart Showing Properties of Asphalt R.

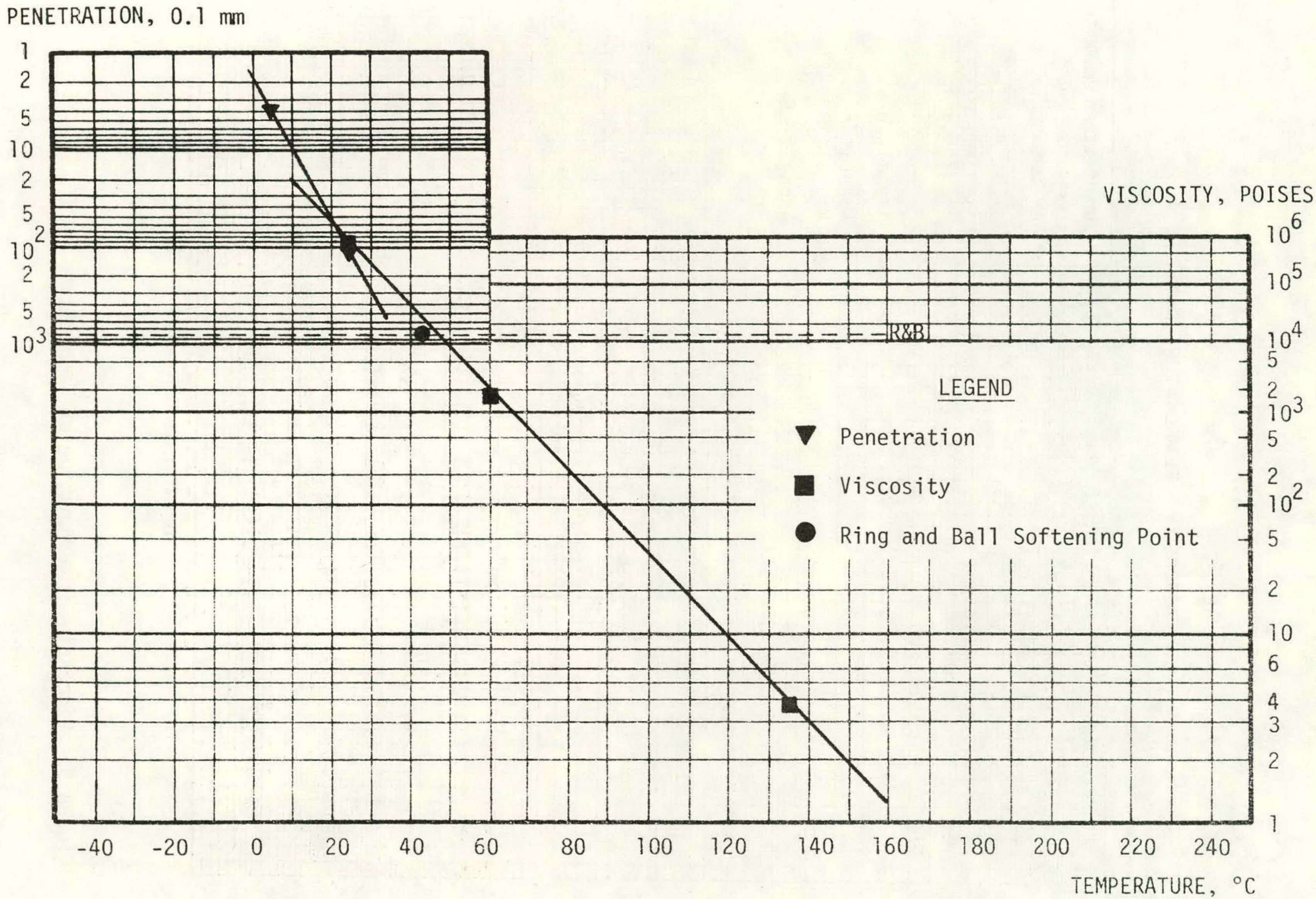

Figure 4. Bitumen Test Data Chart Showing Properties of Asphalt LS.

VISCOSITY - TEMPERATURE CHART

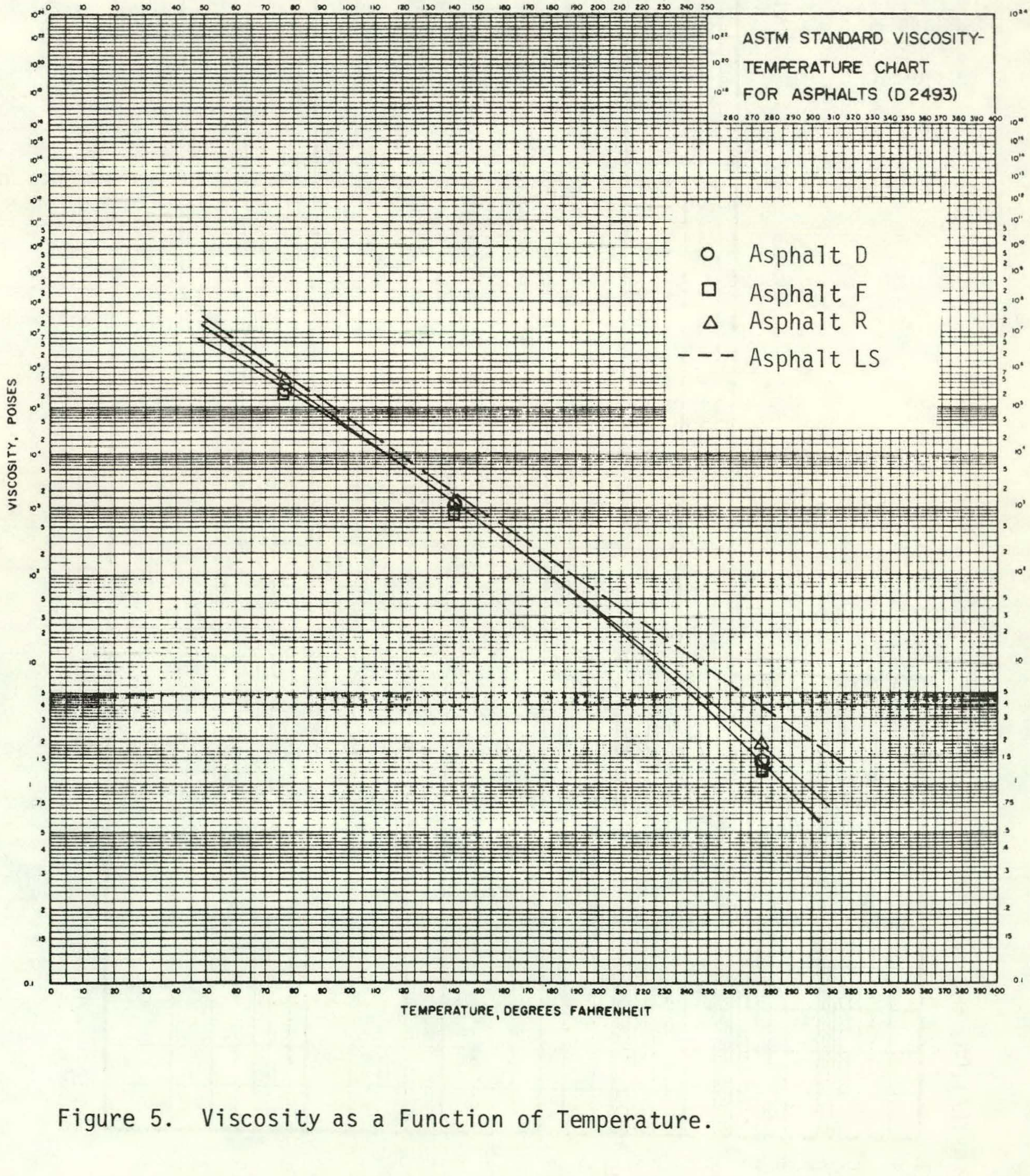

Figure 5. Viscosity as a Function of Temperature.

temperature susceptibility, at least in low temperature ranges. However, temperature susceptibility of the tar sand asphalts increases significantly as temperature increases. This is clearly shown by the slopes of the curves in Figure 5.

Temperature susceptibility is estimated in the high and intermediate temperature ranges using the viscosity-temperature susceptibility (VTS) equation and in more moderate temperature ranges by penetration ratio and penetration index. Pen/Vis number estimates temperature susceptibility over a wide temperature range. (Formulae and explantations are given in Appendix A.) The values of these parameters, shown below, indicate the temperature susceptibilities of the two distilled tar sand asphalts (D and F) are about equal, and temperature susceptibility of the solvent refined asphalt (R) is slightly less. VTS shows the laboratory standard asphalt (LS) to be less temperature susceptible than the tar sand asphalts in the higher temperature range and more temperature susceptible in the lower temperature range.

Parameter	D	F	R	LS
VTS (60 - 135°C)	4.22	4.23	3.95	3.45
VTS (25 - 60°C)	3.50	3.52	3.64	3.61
Penetration Ratio (4-25°C)	28	31	40	22
Penetration Index (25°-42+°C)	+4.3	+3.7	+1.0	-1.4
Pen/Vis Number (25-135°C)	-1.20	-1.20	-0.86	-0.10

It has been shown that the temperature susceptibility of an asphalt depends on the temperature range over which it is determined. The lower temperature susceptibilities of the tar sand asphalts in the lower temperature range is a desirable quality since they indicate asphalts that would not be brittle at low temperatures. The higher temperature susceptibilities in the higher temperature range could probably be accommodated by using appropriate mixing temperatures and construction techniques. Ring and ball softening point data are not consistent with the above mentioned higher temperature susceptibility of the tar sand asphalts at higher temperatures. Observation of the softening points as well as the ductility data indicate significant differences in flow properties of Asphalts D and F and Asphalts R and LS.

An interesting point here is that asphalt temperature susceptibility, particularly in the low temperature range, is dependent upon the method of manufacture. Similar phenomena were observed in Phase I (1) as the three shale oil asphalts were also manufactured by different methods from a single crude source and displayed different temperature susceptibilities.

Figure 5, an ASTM viscosity-temperature chart, exhibits a notable decrease in viscosity at high temperatures for the tar sand asphalts.

The slope of the curves in this plot is, of course, another way of observing asphalt temperature susceptibility and its variation with temperature.

With regard to the similarity of the viscosities, the softening point of Asphalt R is significantly lower than Asphalts D and F, and the ductility is significantly higher. Asphalt R may have contained a greater percentage of lighter hydrocarbons resulting from the method of manufacture, which, may not have been optimized. This idea is supported by the high loss on heating and, consequently, hardening during the thin film oven test (Table 1). Additionally, the flash point and fire point of Asphalt R are also significantly lower than those of Asphalt D and F.

Note that the tar sand Asphalts D and F actually showed an increased ductility after the thin film oven test, whereas, the high volatile loss of Asphalt R resulted in decreased ductility.

Approximately five percent of the tar sand asphalts were insoluble in trichloroethylene. This is probably due to the ash and coke content of the original crude which resulted from the in situ recovery process. Similar reasoning may explain the positive results of the spot test.

The vanadium contents of these tar sand asphalts are low when compared to sixty-five asphalts tested by Traxler (8). Therefore, these asphalts may be expected to resist surface hardening due to sunlight. This deduction is supported by the very low hardening indices that were determined from the actinic light hardening test.

According to Heukelom (7), when the penetration plot on the Bitumen Test Data chart are parallel and the penetration plot is offset toward the lower penetrations, the asphalt contains wax. The distilled tar sand asphalts (D,F) appear to fall in this category (Figures 1 and 2). However, the solvent separation process has apparently removed the wax from Asphalt R (Figure 3).

These tar sand asphalts are atypical and exhibit some desirable as well as undesirable characteristics. When compared to AASHTO specification M226 (9), the following anomalities were encountered with the tar sand asphalts:

1. Asphalts D and F exhibited viscosities at 275°F (135°C) lower than the specified value. However, this could likely be rectified by supplying a slightly harder asphalt within the 140°F (60°C) viscosity limits.

2. None of the asphalts passed the solubility in trichloroethylene specification.

3. Loss on heating of all the asphalts exceeded the maximum specified value, particularly for Asphalt R.

4. The viscosity of 140°F (60°C) of Asphalt R after the thin film

oven test greatly exceeded the maximum specified value. This would most certainly eliminate it from use in paving applications unless adjustments could be made in the production process to diminish this problem.

5. Asphalts D and R barely meet the specification for ductility at 77°F (25°C) after the thin film oven test.

Although temperature susceptibilities are considered high, the unusually high penetrations may offset any anticipated pavement performance problems at low temperatures. On the other hand, low ductility values of Asphalts D and R, especially after the thin film oven test, cause one to anticipate low-temperature pavement performance problems. Low solubilities and positive spot tests result from the content of ash and coke. It should be determined whether or not the presence of the insolubles will cause problems in paving mixtures or if they can be eliminated in a full-scale production process.

AGGREGATE PROPERTIES

Prior to discussing the mixture properties contributed by asphalt cements the basic characteristics of the aggretates should be presented. The two types of aggregates selected for use in this research study are laboratory standard aggregates at the Texas A&M University materials laboratory (10).

The subrounded, siliceous gravel was obtained from a Gifford-Hill plant near the Brazos River at College Station, Texas. A very hard crushed limestone was obtained from White's Mines at a quarry near Brownwood, Texas. Standard sieves (ASTM E-11) were used to separate the aggregates into fractions sized from 3/4 inch to minus No. 200 mesh. Prior to mixing with asphalt, the various aggregate sizes were recombined according to the ASTM D 3515-77 5A grading specification. Standard tests were conducted to determine various physical properties of these aggregates such as specific gravity, absorption capacity, abrasion resistance, and unit weight. One additional test (11) was conducted to estimate the optimum asphalt content.

The types of tests and results are presented in Table 2.

TAR SAND ASPHALTS IN PAVING MIXTURES

Optimum Asphalt Content

During Phase I of this research a comprehensive study was conducted using the laboratory standard asphalt (LS) to determine the optimum asphalt contents for the two different laboratory standard aggregates, gravel and limestone. The test program and results are described in

Table 2. Physical Properties of Aggregates.

Physical Property	Designation	Aggregate Grading	Test Results	
			Gravel	Limestone
Bulk Specific Gravity Bulk Specific Gravity (SSD) Apparent Specific Gravity Absorption	ASTM C 127 AASHTO T 85	Course* Material	2.621 2.640 2.672 0.72	2.663 2.678 2.700 0.7
Bulk Specific Gravity Bulk Specific Gravity (SSD) Apparent Specific Gravity Absorption, percent	ASTM C 218 AASHTO T 84	Fine** Material	2.551 2.597 2.675 1.8	2.537 2.597 2.702 2.2
Bulk Specific Gravity Apparent Specific Gravity Absorption, percent	ASTM C 127 & C 128 AASHTO T 84 & T 85	Project Design Gradation	2.580 2.671 1.3	2.589 2.701 1.56
Abrasion Resistance, percent loss	ASTM C 131 AASHTO T 96	Grading C	19	23
Compacted Unit Weight, pcf	ASTM C 29 AASHTO T 19	Project Design Gradation	129	122
Surface Capacity, percent by wt. dry aggregate	Centifuge Kerosene Equivalent	Fine** Material	3.0	4.1
Surface Capacity, percent oil retained by wt. agg.	Oil Equivalent	-3/8 inch to + No. 4	1.8	2.3
Estimated Optimum Asphalt Content, percent by wt. dry aggregate	C.K.E. and Oil Equivalent	Project Design Gradation	4.7	5.5

*Material retained on No. 4 sieve from Project Design Gradation.

**Material passing No. 4 sieve from Project Design Gradation.

detail in Appendix B. Since the aggregates used in Phase II were identical to those used in Phase I, identical asphalt contents were utilized when mixing each of the tar sand asphalts with these aggregates. Identical asphalt contents were necessary in order to make direct comparisons of such qualities as tensile strength and water susceptibility. The design asphalt contents were 3.8 percent with river gravel and 4.5 percent with crushed limestone.

Test Results on Gyratory Compacted Specimens

Testing of Gyratory compacted specimens was conducted in accordance with the program described in Figure 6.

Resilient Modulus. As shown in Figure 6, thirty-three specimens were fabricated using each asphalt-aggregate mixture in accordance with Test Method TEX-206-F (12). The resilient modulus of each of these specimens was measured at 68°F (20°C) using the Schmidt device (13) which employs a loading duration of 0.1 seconds. The test results are given in Table 3 and a histogram is provided in Figure 7. Results for the individual specimens are tabulated in Appendix C.

The resilient moduli of the specimens made with Asphalts D and F were significantly lower than the resilient moduli of those made with Asphalts R and LS. Hardening of Asphalt R during mixing and molding is probably the reason for the larger values of resilient modulus. Evidence supporting this postulation are the comparative penetrations at 25°C after the thin film oven test which indicate a similar order of asphalt stiffness.

Specimens made with tar sand asphalt exhibited significantly lower resilient moduli at 68°F (20°C) than those made with shale oil asphalt in Phase I (1). The differences appear to be directly related to viscosity and/or penetration measurements at lower temperatures.

Resilient modulus was also measured at -13, 33, 77 and 104°F (-25, 1, 25, and 40°C, respectively). These data are presented in Appendix C. As expected, the stiffness values at the lower temperature approach similar values for similar aggregates (Figures 8 and 9). At the high temperature end, the slopes of the curves begin to decrease, as expected. An inflation point for these curves is located at approximately 75°F (24°C). Since the aggregates within each figure are identical, these phenomena can be related to the viscosities of the asphalts. At the highest temperatures, the crushed material, of course, produce the stiffer mixtures, however, at the lowest temperatures, the gravel produced the stiffer mixtures. This is probably due to the higher modulus of the gravel particles.

Water Susceptibility. Following the resilient modulus test, specimens were submerged in water and vacuum saturated at one inch (25mm) of mercury (absolute pressure) for two hours and allowed to soak at atmospheric pressure for seven days. While saturated with water, the resilient modulus of each specimen was again measured at 68°F then the

Table 3. Resilient Modulus of Gyratory Compacted Specimens @ 68° F (20°C)

Aggregate	Asphalt	Mean psi x 10^6	Standard Deviation	Coef. of Variation, percent
Gravel	D	0.33	0.067	20
	F	0.32	0.039	12
	R	0.63	0.131	20
	LS	0.51	0.059	12
Limestone	D	0.49	0.055	11
	F	0.48	0.055	12
	R	0.73	0.115	16
	LS	0.72	0.100	14

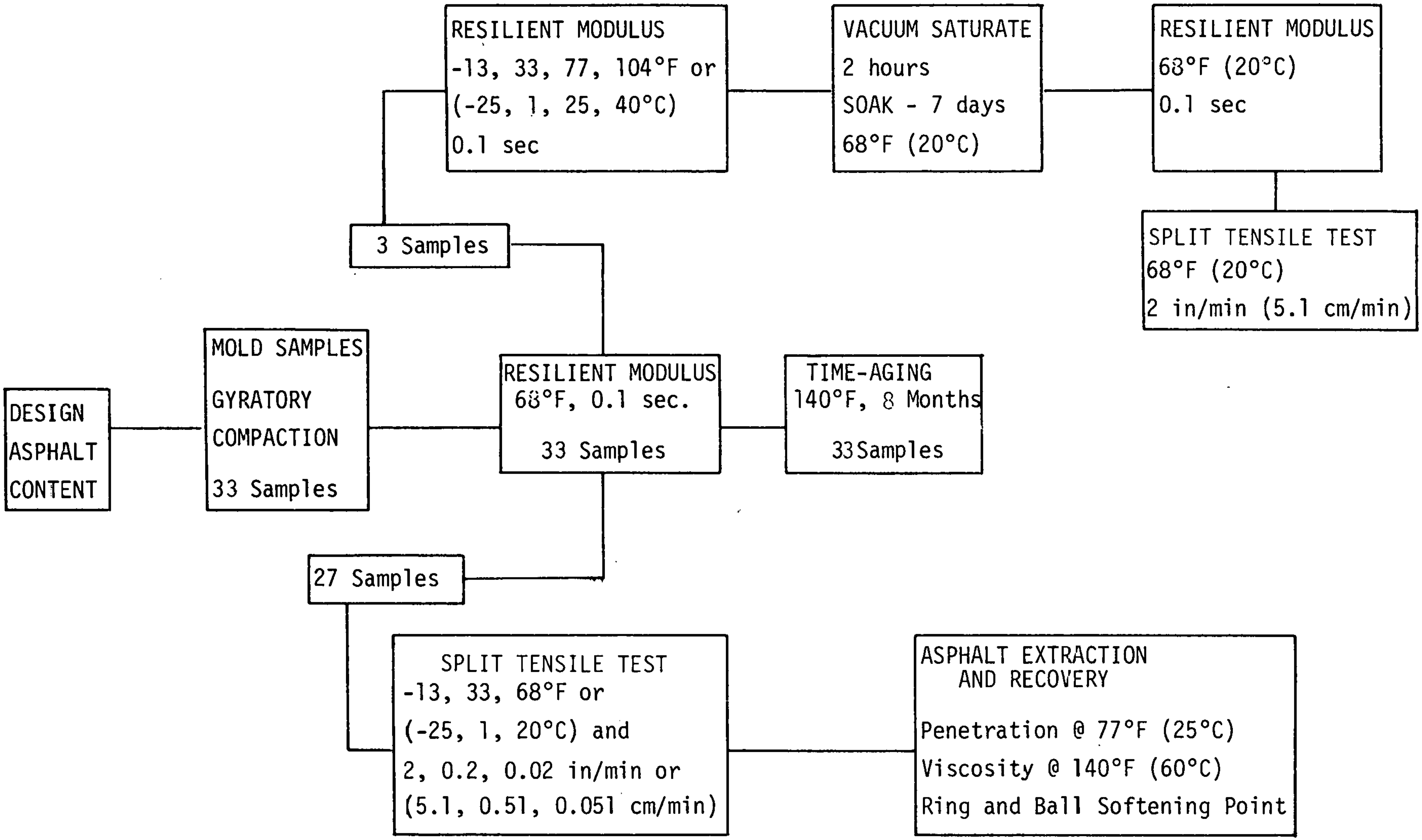

Figure 6. Test Program to Determine Strength and Water Susceptibility of Mixtures.

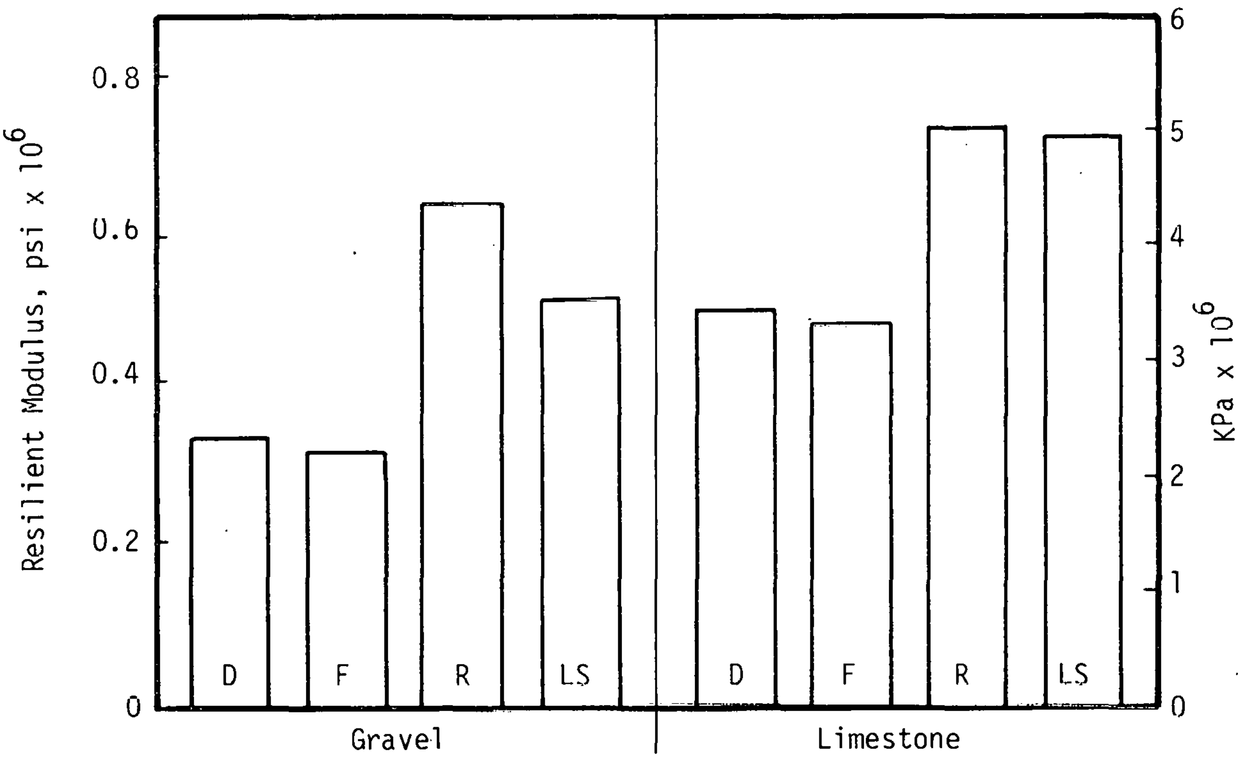

Figure 7. Mean Resilient Modulus of All Test Specimens at 20°C (68°F)

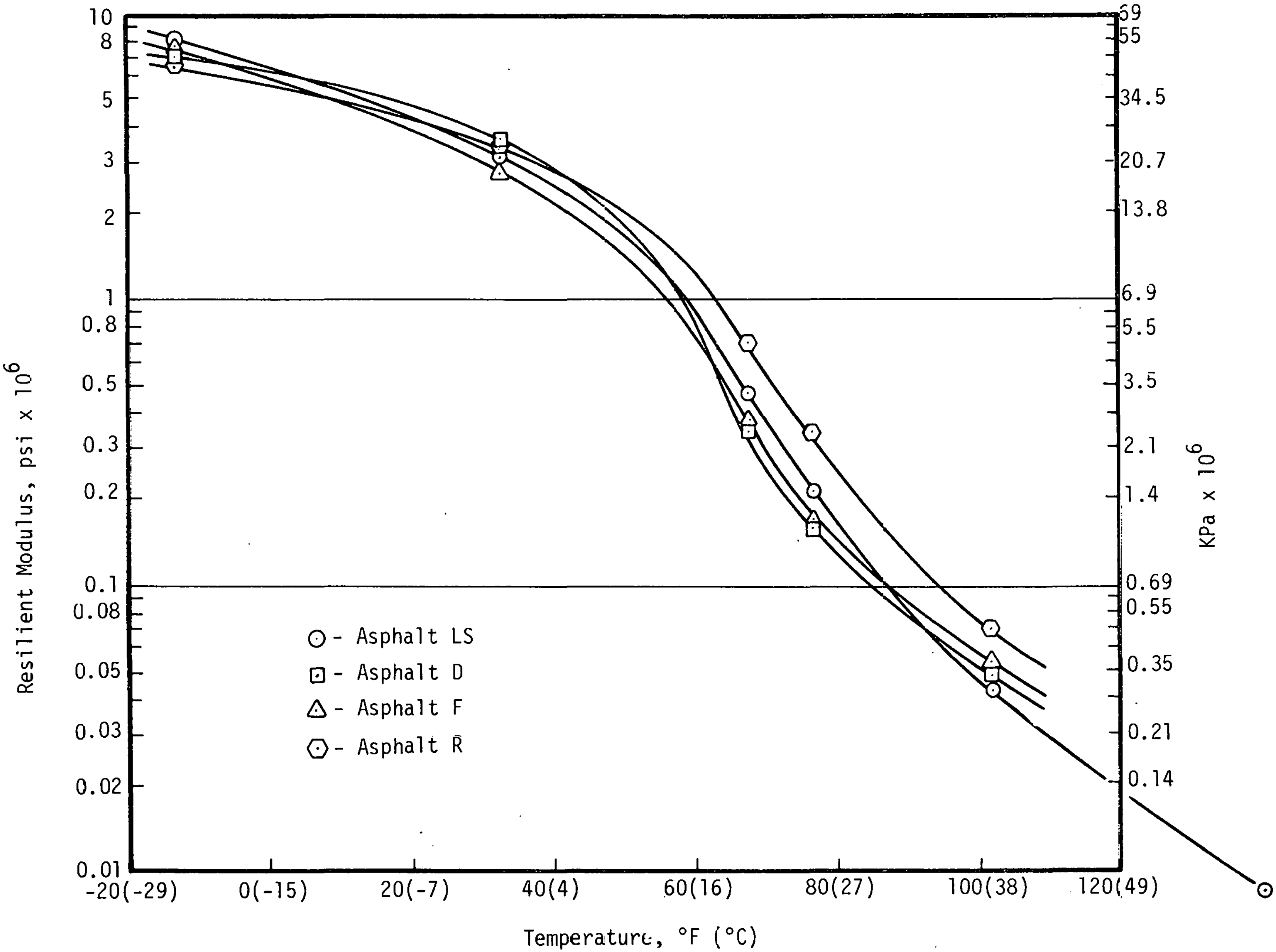

Figure 8. Resilient Modulus as a Function of Temperature of Specimens Containing Gravel

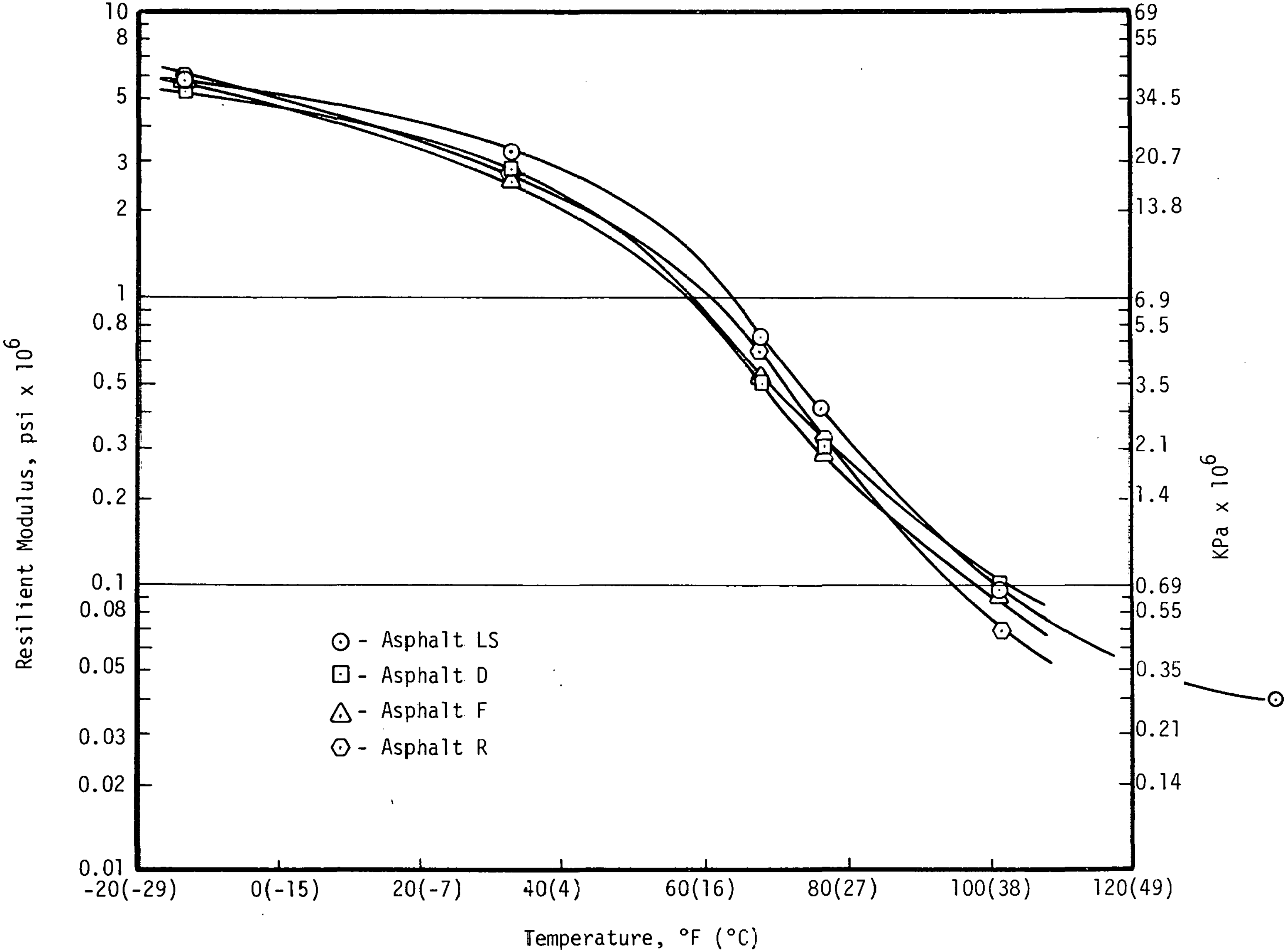

Figure 9. Resilient Modulus as a Function of Temperature of Specimens Containing Limestone

splitting tensile test was conducted at 68°F and 2 inches per minute (5.1 cm/min). Resilient moduli from these tests are tabulated in Appendix E and splitting tensile test results are tabulated in Table D7 of Appendix D. Summaries of splitting tensile data and resilient before and after soaking are given in Tables 4 and 5, respectively. Histograms to facilitate comparisons are given in Figures 10 through 13.

Resilient modulus ratios (Table 5) and Figures 10 and 11 indicate that all the specimens experienced a decrease in stiffness after exposure to moisture. Tensile strength ratios and Figures 12 and 13, on the other hand, indicate that Asphalts D and F were quite resistant to moisture damage while Asphalts R and LS were notably weakened upon exposure to moisture. Mixtures containing Asphalt R always had the lowest tensile strength after soaking, although it was usually highest before soaking (Table 4). This is consistent with the shale oil asphalt data of Phase I (1) in that the distilled Asphalts (D and F) exhibited little water susceptibility and the solvent separated Asphalt R exhibited significantly more water susceptibility. The tar sand asphalts contain an average of about 1.2 percent nitrogen. This is higher than most petroleum asphalts. These data add support to the postulation in Reference 1 that basic nitrogen improves an asphalts resistance to damage by moisture and that the solvent process possibly removes certain compounds in the tar sand asphalts that would otherwise aid in preventing moisture damage. Admittedly, more data would be required in order to make positive statements regarding water susceptibility.

Tensile Strength. Twenty-seven of the thirty specimens of each type were selected and divided into three groups of nine each and conditioned at temperatures of -13, 33, 68°F (-25, 1, 20°C, respectively). Then they were subdivided into groups of three each and the splitting tensile test was conducted at loading head displacement rates of 2, 0.2, 0.02 inches per minute (5.1, 0.51, 0.051 cm/min). Test results for individual specimens and plots of stress at failure and secant modulus as a function of loading rate are given in Appendix D. A summary of the test results is presented in Table 4.

As expected, test results indicated tensile strengths of the mixtures to be a direct function of loading rate and an inverse function of temperature. And of course the specimens containing crushed limestone usually exhibited greater tensile strengths and elastic moduli than their counterparts containing rounded gravel.

At each test condition (except after soaking) Asphalt R produced mixtures with the highest or near the highest tensile strengths and secant moduli. This is likely a result of asphalt hardening during the mixing and compacting procedure. Asphalts D and F usually produced mixtures with similar tensile strengths and secant moduli which were usually lower than those containing either Asphalt R or LS. This too appears to be directly related to the recovered asphalt properties which will be discussed later.

The mode of failure of the splitting tensile test specimens ranged from ph sically unnoticeable at 68°F (20°C) and 0.02 in/min (0.051 cm/min)

Table 4. Summary of Splitting Tensile Data.

Aggregate	Disp. Rate in/min (cm/min)	Temp. °F(°C)	Asphalt D			Asphalt F			Asphalt R			Asphalt LS		
			Stress, psi	Strain, in/in	Modulus, psi x 10^3	Stress, psi	Strain, in/in	Modulus, psi x 10^3	Stress, psi	Strain, in/in	Modulus, psi x 10^3	Stress, psi	Strain, in/in	Modulus, psi x 10^3
Gravel	2.0 (5.1)	68 (20)	70	0.0029	25	70	0.0039	18	120	0.0027	46	110	0.0029	38
		33 (1)	400	0.0016	260	430	0.0015	298	450	0.0034	278	390	0.0027	170
		-13 (-25)	390	0.0004	2,020	450	0.0004	3,400	480	0.0002	4,570	490	-	-
	Soak	68 (20)	100	0.0059	18	73	0.0059	16	69	0.0030	24	100	0.0054	21
	0.2 (0.51)	68 (20)	30	0.0031	11	30	0.0029	10	50	0.0033	16	50	0.0043	12
		33 (1)	170	0.0032	68	150	0.0033	121	290	0.0018	192	250	0.0020	130
		-13 (-25)	340	0.0002	2,030	500	-	-	510	0.0002	3,000	380	-	-
	0.02 (0.051)	68 (20)	15	0.0033	4	15	0.0037	5	25	0.0033	7	20	0.0041	5
		33 (1)	60	0.0022	32	55	0.0020	29	100	0.0019	59	110	0.0018	59
		-13 (-25)	325	-	-	440	0.0003	2,370	450	0.0003	1,550	340	-	-
Limestone	2.0 (5.1)	68 (20)	85	0.0045	24	35	0.0023	39	140	0.0025	55	150	0.0035	60
		33 (1)	520	0.0014	392	420	0.0020	288	510	0.0008	675	520	0.0018	290
		-13 (-25)	730	-	-	850	0.0002	5,890	740	0.0002	5,120	630	-	-
	Soak	63 (20)	120	0.0034	35	110	0.0054	22	63	0.0036	18	90	0.0059	16
	0.2 (0.51)	68 (20)	40	0.0029	14	35	0.0028	13	80	0.0029	29	90	0.0041	23
		33 (1)	250	0.0026	159	230	0.0017	133	370	0.0019	310	310	0.0022	150
		-13 (-25)	570	0.0002	3,910	570	0.0002	3,760	560	0.0003	3,510	630	-	-
	0.2 (0.051)	68 (20)	20	0.0041	6	20	0.0041	6	30	0.0040	9	40	0.0040	11
		33 (1)	90	0.0022	42	55	0.0013	52	130	0.0017	85	140	0.0021	70
		-13 (-25)	550	0.0003	1,430	500	0.0004	1,420	560	0.0004	1,290	410	-	-

1 psi = 6.895 kPa

Table 5. Summary of Data from Water Susceptibility Study.

Aggregate	Asphalt	Air Void Content, Percent	Resilient Modulus psi x 10^6		Resilient Modulus Ratio*, Percent	Tensile Strength Ratio*, Percent
			Before	After		
Gravel	D	1.8	0.328	0.183	0.56	1.43
	F	1.8	0.369	0.231	0.63	1.04
	R	1.6	0.695	0.611	0.88	0.56
	LS	2.8	0.460	0.300	0.65	0.91
Limestone	D	1.6	0.497	0.451	0.91	1.41
	F	1.5	0.523	0.475	0.91	1.29
	R	1.6	0.634	0.576	0.91	0.45
	LS	3.6	0.750	0.450	0.60	0.60

1 psi = 6.895 kPa

*Computed by dividing result after soaking by result before soaking.

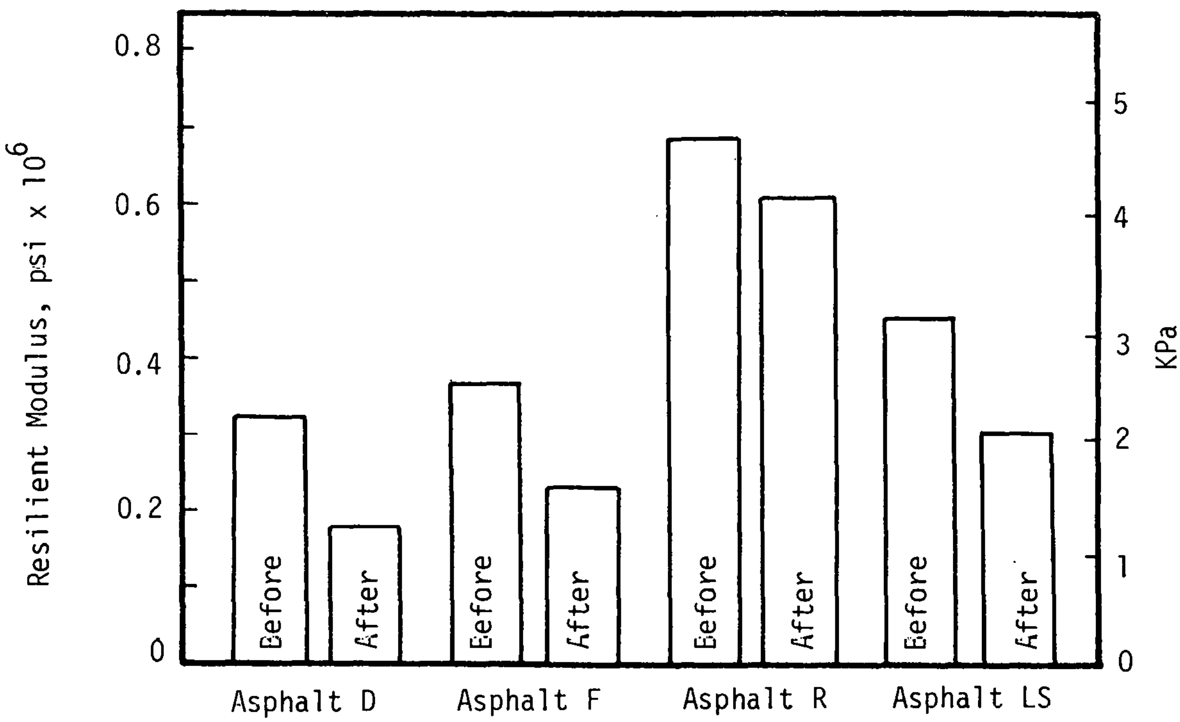

Figure 10. Resilient Modulus at 68°F (20°C) of Gravel Specimens Before and After Soaking

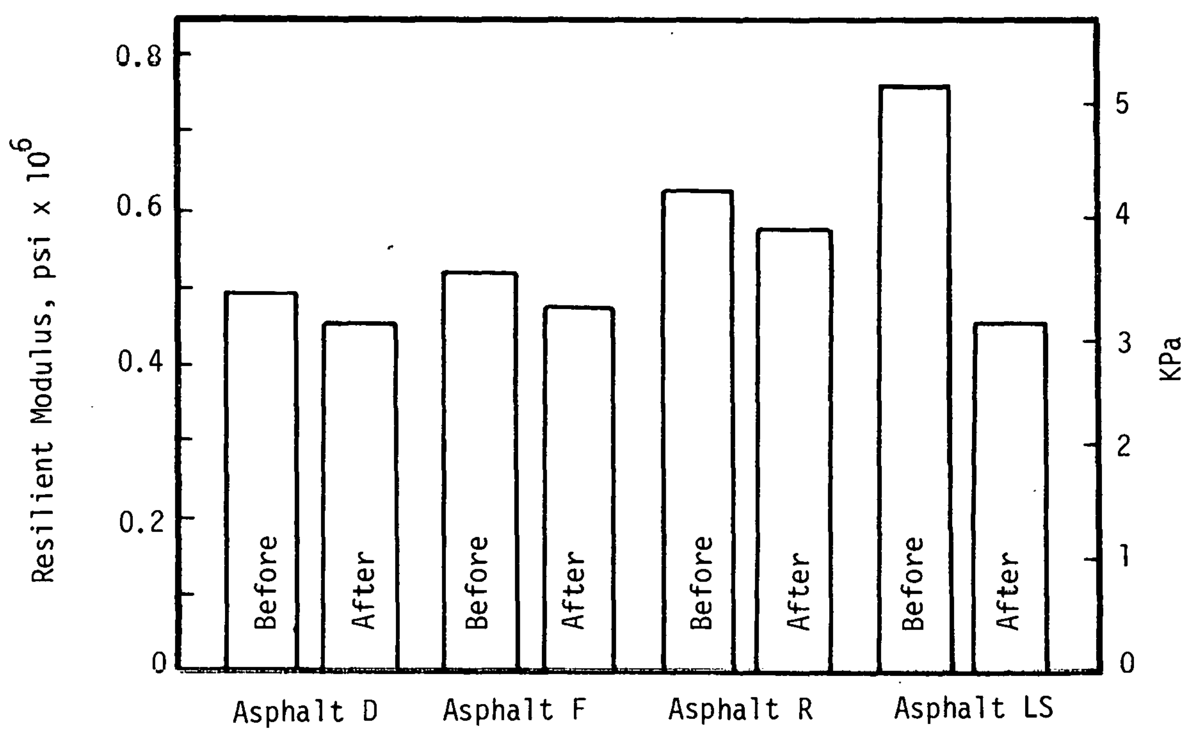

Figure 11. Resilient Modulus at 68°F (20°C) of Limestone Specimens Before and After Soaking

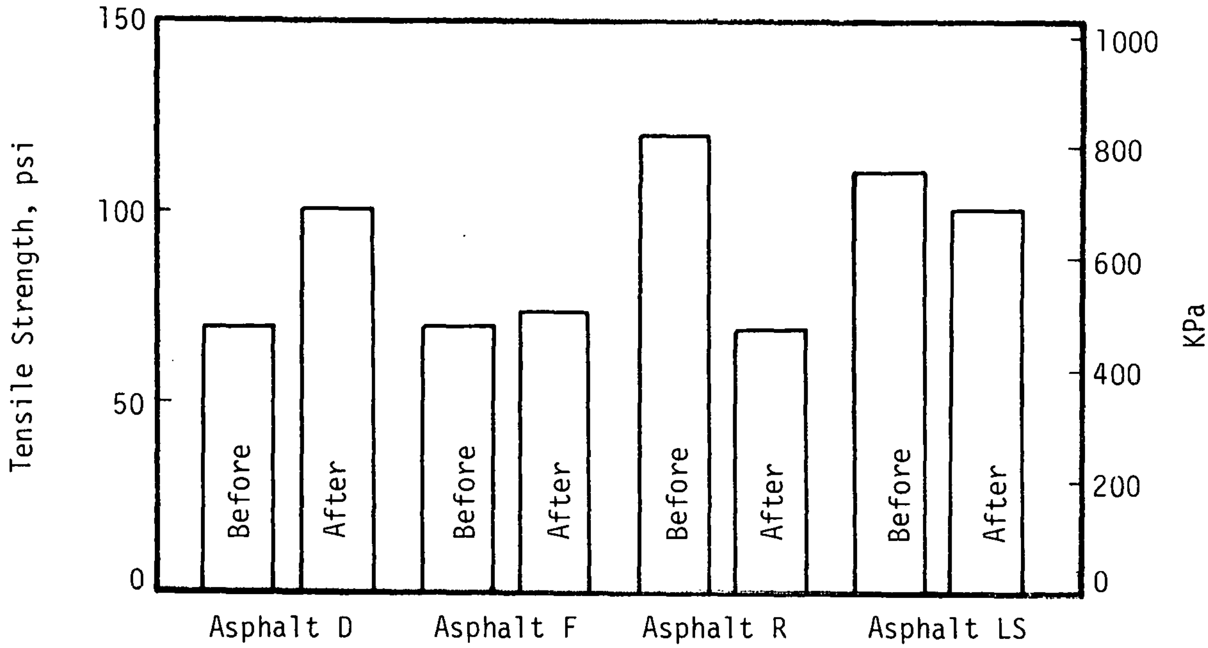

Figure 12. Tensile Strength of Gravel Specimens at 68°F (20°C) Before and After Soaking

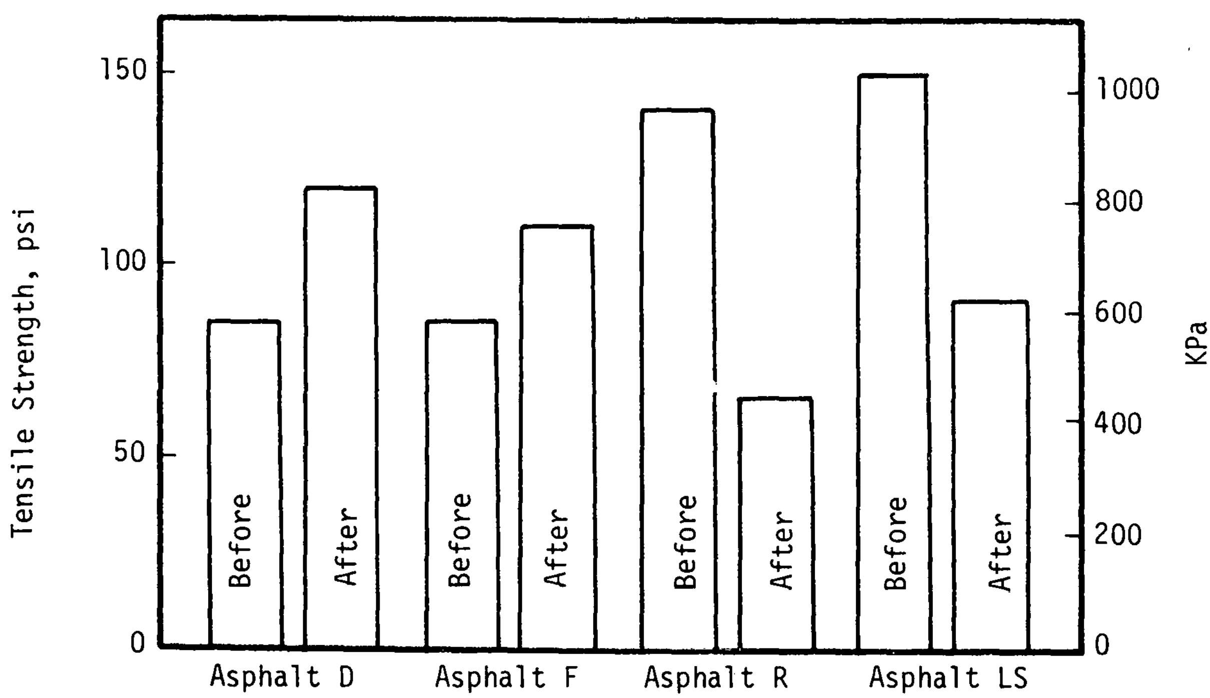

Figure 13. Tensile Strength of Limestone Specimens at 68°F (20°C) Before and After Soaking

to catastropic at -13°F (-25°C) and 2 in/min (5.1 cm/min). At -13°F the failure plane was well defined such that the larger aggregate particles within the failure plane were severed, indicating the tensile strength of the matrix was near or greater than that of the individual aggregate particles.

Inspection of Figures D1 through D12 in Appendix D shows no noticeable differences in behavior of the tar sand asphalts when compared to the petroleum asphalt, except in modulus at -13°F (-25°C). Figures D3 and D6 show the secant modulus of mixtures containing Asphalt LS to be significantly less than the mixtures containing the tar sand asphalts. Splitting tensile data for mixtures containing Asphalt LS were obtained during Phase I of this study using a cantilever beam device containing strain gages to monitor lateral deformation of the specimens. Subsequent equipment modifications prior to Phase II included replacement of this device with a twin linear variable differential transformer (LVDT), a more dependable system, particularly at very low temperatures.

Recovered Asphalt Properties. Extraction of the tar sand asphalts from selected laboratory specimens was conducted in accordance with ASTM D-2172 (Method B) using a solvent consisting of 95 percent trichloroethylene and 5 percent ethanol. After centrifuging the extraction mixture, each of the three solutions of solvent with tar sand asphalt contained a black substance with a consistency of soft butter floating on top of the solution. The identity of this substance is unknown but merely mentioned here because of its abnormality and its association with tar sand asphalts. Recovery of the asphalts was achieved by poring the extracted solution into a boiling flask and heating it for one hour at 295°F (146°C) under an absolute pressure of 2 inches (50.7 mm) of Hg. Properties of the asphalts obtained from gravel as well as limestone are given in Table 6.

All test results indicate Asphalt R hardened significantly more than any of the other asphalts and, generally, Asphalt LS hardened more than Asphalt D and F. The distilled tar sand asphalts are shown to be comparatively resistant to hardening during mixing and compacting of paving mixtures, whereas, the solvent produced asphalt is not. In Phase I of this research, the shale oil asphalts demonstrated similar trends (1). As previously indicated, hardening of the solvent processed asphalt probably resulted from excess volatiles; sufficient crude was not available to optimize the preparation process.

Aging Characteristics. Three specimens were fabricated from each of the three tar sand asphalts and the two aggregates (18 specimens). Following the resilient modulus test at 68°F, they were aged for eight months at 140°F (Figure 6). Then the resilient modulus and splitting tensile test were performed to determine their relative aging characteristics. Test results are summarized in Table 7.

An aging index (Table 7) was computed by dividing the resilient modulus after aging by the original value. Asphalt R was found to not only produce stiffer mixtures, originally, but also to continue hardening at a faster rate than Asphalts D and F.

Table 6. Recovered Asphalt Properties.

Source	Test	Asphalt D	Asphalt F	Asphalt R	Asphalt LS
Extracted from Gravel	Penetration @ 77°F, dmm	101	91	45	55
	Viscosity @ 77°F, poise	7.2×10^5	1.0×10^6	4.1×10^6	3.9×10^6
	Viscosity @ 140°F, poise	1700	1780	5790	4630
	R&B Softening Point, °F (°C)	138(59)	149(61)	141(61)	129(54)
Extracted from Limestone	Penetration @ 77°F, dmm	103	120	55	53
	Viscosity @ 77°F, poise	4.0×10^5	4.0×10^5	2.6×10^6	3.8×10^6
	Viscosity @ 140°F, poise	1920	1360	3920	4320
	R&B Softening Point, °F (°C)	150(65)	141(61)	137(59)	128(54)

Table 7. Effects of Aging Eight Months @ 140°F.

Aggregate	Asphalt	Resilient Modulus* @ 68°F (20°C) psi x 10^6		Aging Index** (Res. Mod.)	Splitting Tensile Test			Tensile Strength Ratio**	Tensile Modulus Ratio**
		Original	Aged		Failure Stress, psi	Failure Strain, in/in	Secant Modulus, psi x 10^3		
Gravel	D	0.433	1.21	2.8	176	0.00018	1055	2.5	42
	F	0.335	0.95	2.8	175	0.00021	834	2.5	46
	R	0.495	2.49	5.0	294	0.00015	2050	2.5	45
Limestone	D	0.454	1.15	2.5	187	0.00019	975	2.2	41
	F	0.512	1.13	2.2	205	0.00018	1217	2.4	36
	R	0.702	2.00	2.8	350	0.00014	2900	2.5	49

*Average for three specimens tested at 2 in/min and 68°F.

**Value after aging divided by original value.

1 psi = 6.895 kPa

Tensile strength and secant modulus before and after aging were also compared by dividing their values after aging by corresponding original values (Table 7). Results are generally consistent with the aging index discussed previously, but show less contrast between Asphalt R and the other two tar sand asphalts.

Stability and Compactibility

Three specimens of each type were compacted using the Marshall method (ASTM D-1559) and the Texas gyratory (TEX-206-F, Part II) (12) and tested in accordance with program shown in Figure 14.

Marshall Compacted Specimens. Test results for the Marshall compacted specimens are given in Table 8. The Marshall stability of all the mixtures exceeded the value of 500 pounds which has been established as a minimum by the Asphalt Institute (14). Observation of values for voids in the mineral aggregate (VMA) indicate all mixtures were about equal in compactability. In fact, all the characteristics observed were quite similar for mixtures containing the same aggregate which implies that satisfactory performance of the tar sand asphalts can be expected.

Gyratory Compacted Specimens. Test results for the gyratory compacted specimens are given in Table 9. Hveem stability was determined in accorcance with the Texas State Department of Highways and Public Transportation Test Method TEX-208-F, which is a modification of ASTM D-1560. Hveem stabilities were generally borderline according to the Asphalt Institute's specifications. One should normally expect significantly higher stabilities for crushed stone than for the subrounded gravel. The comparatively low stabilities exhibited by Asphalts D and R are inexplicable. Compactibility, as indicated by the voids in the mineral aggregate, is about the same for all mixtures. Resilient moduli agree with earlier test results which shows that Asphalt R produced the stiffest mixtures.

Table 8. Test Results for Marshall Compacted Specimens.*

Aggregate	Gravel				Limestone			
Asphalt Cement	D	F	R	LS	D	F	R	LS
Bulk Specific Gravity	2.44	2.44	2.43	2.44	2.47	2.47	2.47	2.45
Max Specific Gravity	2.49	2.49	2.49	2.49	2.52	2.52	2.52	2.53
Asphalt Absorption, % by wt. aggr.	0.81	0.81	0.79	0.75	1.6	1.6	1.6	1.7
Effective Asphalt Cont., % total mix	2.9	2.9	2.9	2.9	2.8	2.8	2.8	2.6
Voids in Mineral Aggr., % bulk volume	2.0	2.0	2.3	2.1	1.9	1.8	1.8	3.0
VMA filled w/Asphalt, % VMA	82	82	79	80	85	86	86	78
Resilient Modulus @ 68°F, psi x 10^6	0.35	0.28	0.57	0.57	0.50	0.50	0.65	0.59
Marshall Stability, lbs.	1140	1115	1365	1270	2310	2130	2260	2740
Marshall Flow, 0.01 in.	6	8	7	7	11	11	13	11

*Average Values for three specimens

1 psi = 6.895 kPa

1 in = 25.4 mm

Table 9. Test Results for Gyratory Compacted Specimens.*

Type of Aggregate / Type of Asphalt Cement	Rounded Gravel D	Rounded Gravel F	Rounded Gravel R	Rounded Gravel LS	Crushed Limestone D	Crushed Limestone F	Crushed Limestone R	Crushed Limestone LS
Bulk Specific Gravity of Compacted Mix	2.43	2.43	2.44	2.43	2.47	2.47	2.47	2.46
Maximum Specific Gravity of Mixture	2.49	2.49	2.48	2.50	2.51	2.52	2.51	2.52
Asphalt Absorption, percent by wt. agg.	0.81	0.88	0.75	1.0	1.4	1.5	1.4	1.8
Effective Asphalt Content, percent total mix	2.9	2.8	2.9	2.7	3.0	2.9	3.0	2.6
Voids in Mineral Aggregate, percent bulk volume	9.3	9.3	8.9	9.3	8.7	8.7	8.7	9.1
Air Void Content, percent total volume	2.4	1.9	1.6	2.8	1.4	1.9	1.7	2.5
VMA Filled with Asphalt, percent VMA	74	82	85	76	88	85	86	81
Resilient Modulus, psi x 10^6	0.34	0.41	0.58	0.52	0.34	0.46	0.55	0.59
Hveem Stability	29	31	29	27	31	48	29	54

*Each value represents an average for three specimens.

1 psi = 6.895 kPa

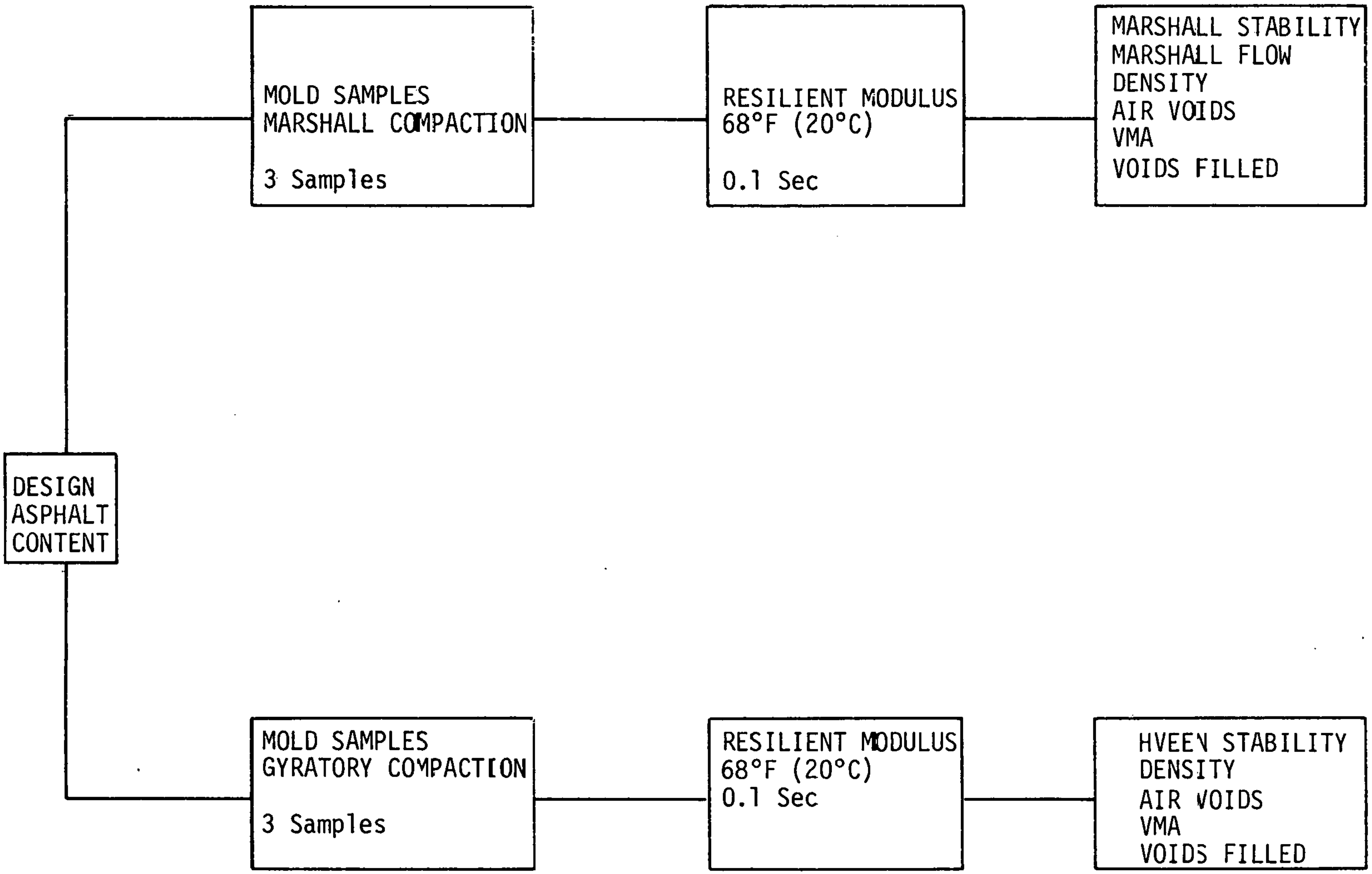

Figure 14. Test Program to Determine Stability and Compactibility of Mixtures.

CONCLUSIONS

From the foregoing research on tar sand asphalts, the following conclusions appear warranted:

1. Paving grade asphalts from tar sand syncrude can be produced by conventional methods.

2. Difficulties may be encountered in passing standard AASHTO specifications such as viscosity at 275°F (135°C), solubility in trichloroethylene, and loss on heating. (Insoluable matter is ash and coke from the in situ mining process.)

3. The temperature susceptibility is comparatively high at higher temperatures and low at lower temperatures.

4. These asphalts may be expected to resist age hardening. Low vanadium content may in part explain the low hardening rates observed.

5. Paving mixtures containing tar sand asphalts produced by distillation show superior resistance to damage by water.

6. Tar sand asphalt produced by the solvent process exhibits excessive hardening upon heating and is significantly more water susceptible than those produced by distillation. These undesirable properties may result from excessive volatiles in the asphalt because it was not possible to otimize the asphalt preparation process.

7. Adhesive properties of tar sand asphalts in paving mixtures is adequate.

8. Stiffness as a function of temperature of mixtures made with tar sand asphalt is comparable to mixtures containing the petroleum asphalt.

9. Stability of mixtures made with tar sand compares well with stability of those made with petroleum asphalt.

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APPENDIX A

Formulae for Computing Temperature Susceptibility

FORMULAE FOR COMPUTING TEMPERATURE SUSCEPTIBILTY

1. Viscosity Temperature Susceptibility (VTS)

$$= \frac{\log \log (100_{\eta_1}) - \log \log (100_{\eta_2})}{\log T_2 - \log T_1}$$

where η = viscosity, poises
T = temperature, °K

(Greater slope means greater temperature susceptibility.)

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2. Penetration Ratio: PR, percent

$$= \frac{\text{Penetration @ 39.2°F (200gm @ 60 sec)}}{\text{Penetration @ 77°F (100gm @ 5 sec)}} \times 100$$

(Lower pen ratio means greater temperature susceptibility.)

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3. Penetration Index: PI, percent

$$= \frac{30}{1 + 90\ \text{PTS}} - 10$$

where

$$\text{PTS} = \frac{\log 800 - \log \text{pen @ 77°F}}{\text{R\&B Soft. Pt.} - 77°\text{F}}$$

(Normal asphalt, PI = +2→ -2; low temperature susceptiblity, > +2; high temperature susceptibility, < -2.)

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4. Pen/Vis Number: (77 to 275°F) PVN

$$= \left[\frac{4.258 - 0.7967 \log P - \log x}{0.7951 - 0.1858 \log P}\right] (-1.5)$$

where P = penetration at 77°F (25°C), dmm
X = viscosity at 275°F (135°C), centistokes

(Lower PVN means greater temperature susceptibility.)

5. Pen/Vis Number: (77 to 140°F)

$$PVN' = \left[\frac{6.489 - 1.590 \log P - \log X'}{1.050 - 0.2234 \log P}\right] (-1.5)$$

where P = penetration at 77°F (25°C), dmm

X' = viscosity at 275°F (135°C), poises

(Lower PVN' means greater temperature susceptibility).

APPENDIX B

Determination of Optimum Asphalt Content

DETERMINATION OF OPTIMUM ASPHALT CONTENT (1)

General

One of the first steps in producing asphalt-aggregate mixtures for paving purposes is to determine the optimum asphalt content. The optimum asphalt content for each of the two laboratory standard aggregates was determined using the laboratory standard asphalt. Identical asphalt contents were used when mixing each of the shale oil asphalts with these aggregates, although some design procedures would indicate somewhat different optimums for different viscosities of binder. Determination of optimum asphalt content was accomplished in accordance with the test program shown by the flow chart in Figure B1.

Mixing of Laboratory Standard Asphalt with Aggregate

As mentioned earlier, the various aggregate fractions were recombined to meet specifications. The mixing and compacting temperatures for the asphalt-aggregate mixtures were determined to be 305 ± 5°F (152°C) and 283 ± 5°F (140°C), respectively, by using the test procedure described in ASTM D-1559. (The procedure requires mixing at the temperature that produces an asphalt viscosity of 170 ± 20 centistokes and compacting at the temperature than produces an asphalt viscosity of 280 ± 30 centistokes kinematic). Prior to mixing with asphalt cement, the aggregates were heated a minimum of four hours at 305 ± 5°F. The asphalt cement was heated in the same oven a minimum of 3/4 hour and a maximum of 2 hours. The appropriate quantity of asphalt cement was added to the heated aggregate then the mixture was blended in a mechanical mixer while heat was applied using a Bunsen burner. When blending was completed (all aggregate particles coated with asphalt cement), the mixture was carefully divided into three aliquots of predetermined weight and placed in an oven of appropriate compaction temperature. The mixing and batching operation was completed in approximately four minutes. A data summary of the asphalt-aggregate mixtures is presented in Table B1.

Marshall Compaction and Testing

Compaction and testing were conducted in accordance with ASTM D-1559, "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus". As soon as the temperature of each batch reached 283 ± 5°F (140°C) they were compacted by applying 50 blows in each face of the specimen. When the specimens were sufficiently cool (less than 140°F) they were extruded from the molds. The weight and height of each specimen was accurately measured. The 4-inch (10.2 cm) diameter specimens are about 1200 grams in weight and 2.5-inches (6.4 cm) in height. The bulk specific gravity of each specimen was determined in accordance with ASTM D-2726 "Bulk Specific Gravity of Compacted Bituminous Mixtures Using

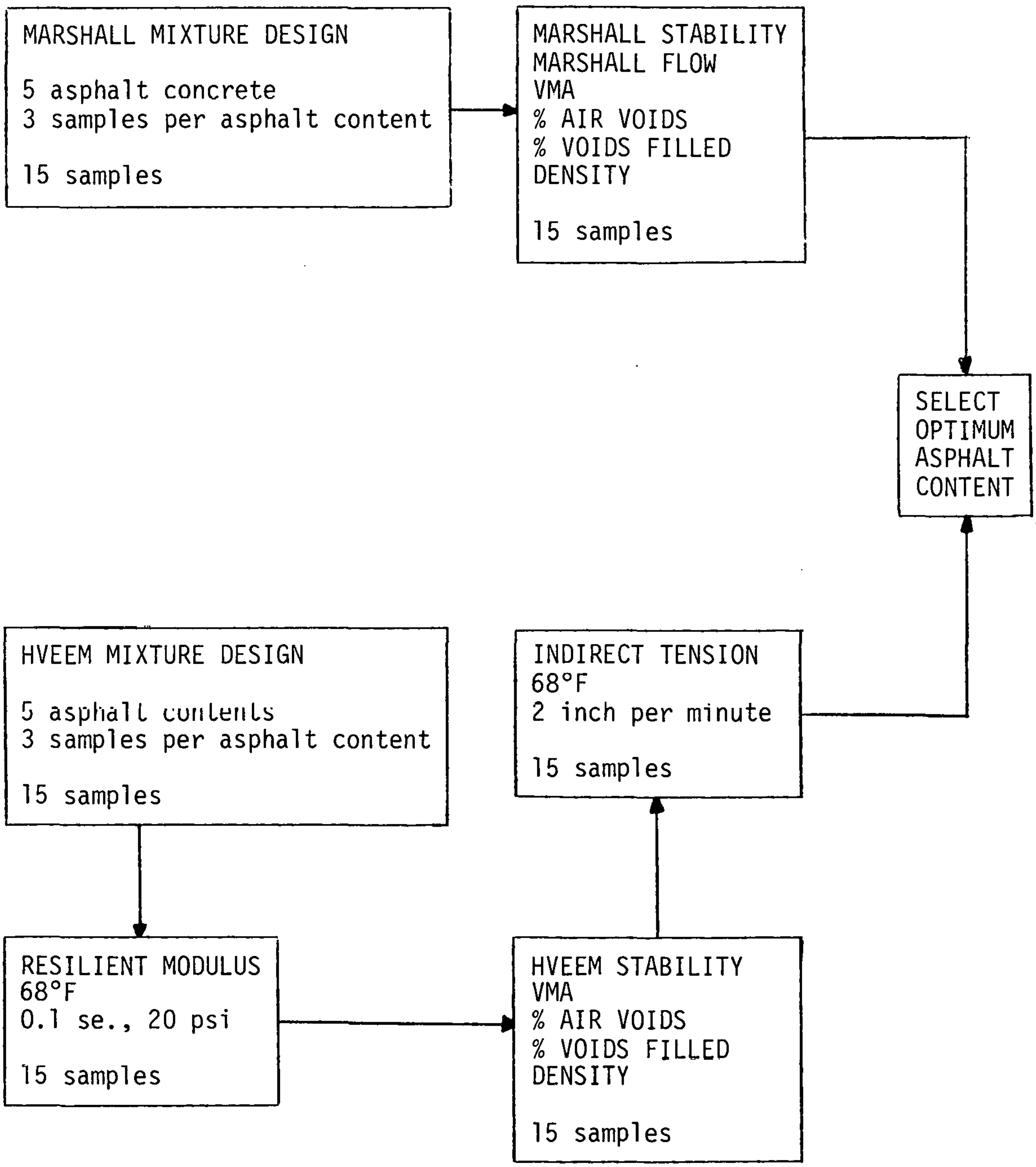

Figure B1. Test Program for Determination of Optimum Asphalt Content.

Table B1. Data Summary of Asphalt-Aggregate Mixtures.

Asphalt Content, Percent by wt. Aggregate	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Asphalt Content, Percent by wt. Total Mix	2.4	2.9	3.4	3.9	4.3	4.8	5.2	5.7
Coarse Aggregate, Percent by wt. Total Mix	41.5	41.3	41.1	40.9	40.7	40.5	40.3	40.1
Fine Aggregate, Percent by wt. Total Mix	50.7	50.5	50.2	50.0	49.8	49.5	49.3	49.1
Mineral Filler, Percent by wt. Total Mix	5.4	5.3	5.3	5.3	5.3	5.2	5.2	5.2
Total Aggregate, Percent by wt. Total Mix	97.6	97.1	96.6	96.2	95.7	95.2	94.8	94.3

Table B2. Summary of Test Results for Marshall Specimens Using Rounded Gravel.

Asphalt Cement Content, Percent by wt. Aggregate	2.5	3.0	3.5	4.0	4.5
Bulk Specific Gravity of Compacted Mix	2.37	2.39	2.42	2.44	2.45
Maximum Specific Gravity of Mixture	2.53	2.52	2.50	2.48	2.46
Effective Specific Gravity of Aggregate	2.63	2.64	2.63	2.63	2.63
Asphalt Absorption, Percent by wt. Aggregate	0.72	0.83	0.81	0.76	0.71
Effective Asphalt Content, Percent by Total Mix	1.7	2.1	2.6	3.1	3.6
Voids in Mineral Aggregate, Percent Bulk Volume	10.5	10.0	9.4	9.0	9.3
VMA Filled w/Aspahlt, Percent VMA	47	57	71	85	95
Air Void Content, Percent Total Volume	6.4	5.1	3.2	1.6	0.6
Marshall Stability, lbs	1190	1150	1220	1290	1160
Marshall Flow, 0.01 in	7	7	7	7	8

Table B3. Summary of Test Results for Marshall Specimens Using Crushed Limestone.

Asphalt Cement Content, Percent by Wt. Aggregate	3.5	4.0	4.5	5.0	5.5
Bulk Specific Gravity of Compacted Mix	2.40	2.41	2.45	2.48	2.48
Maximum Specific Gravity of Mixture	2.55	2.55	2.53	2.50	2.49
Effective Specific Gravity of Aggregate	2.70	2.69	2.71	2.69	2.70
Asphalt Absorption, Percent by wt. Aggregate	1.6	1.5	1.8	1.5	1.6
Effective Asphalt Content, Percent by wt. Total Mix	1.8	2.4	2.6	3.4	3.7
Voids in Mineral Aggregate, Percent Bulk Volume	10.5	10.5	9.4	8.8	9.2
VMA Filled with Asphalt, Percent VMA	57	65	78	94	97
Air Void Content, Percent Total Volume	5.9	4.8	3.0	0.8	0.4
Marshall Stability, lbs	2410	2610	2740	2430	2230
Marshall Flow, 0.01 in	9	9	11	15	14

Saturated Surface-Dry Specimens". Marshall stability tests were conducted on the day following compaction of the test specimens. Some of the previously failed specimens were reheated and finely divided in order to determine the maximum specific gravity of the mixture in accordance with ASTM D-2041 "Maximum Specific Gravity of Bituminous Paving Mixtures".

The Marshall compaction tests were accomplished as an aid to the determination of the optimum asphalt cement content for the given aggregate gradation. A summary of the test results for the Marshall Specimens containing gravel and limestone is presented in Table B2 and B3, respectively. (Each value in the figures and tables represents an average for three tests unless otherwise indicated).

Gyratory Compaction and Testing

The aggregate gradation, asphalt, and mixing procedure used in making the gyratory compacted specimens were identical to those used in making the Marshall specimens. However, compaction was conducted in accordance with Texas State Department of Highways and Public Transportation test method TEX-206-F, Part II, "Motorized Gyratory-Shear Molding Press Operating Procedure"(12).

Upon completion of mixing, each batch was placed in an oven and as soon as the required temperature was attained the mixtures were compacted. This test method required a compaction temperature of 250 ± 5°F (121°C) for all asphalt-aggregate mixtures. When the specimens were sufficiently cool, the weight and height of each were accurately determined. These 4-inch (10.2 cm) diameter specimens were approximately 1000 grams in weight and 2-inches (5.1 cm) in height. The bulk specific gravity of each specimen was determined in accordance with ASTM D-2726.

On the day following compaction the resilient modulus, M_R (a measure of stiffness), was determined for each specimen at 68°F (20°C) using the Mark III Resilient Modulus Device developed by Schmidt (13) A diametral load of approximately 72 lbs (33 kg) was applied for a duration of 0.1 seconds while monitoring the lateral deformation.

The Hveem stability of the specimens was determined in accordance with the Texas State Department of Highways and Public Transportation test method TEX-208-F "Test for Stabilometer Value of Bituminous Mixtures", which is a modification of ASTM D-1560.

The final test performed on these specimens was the splitting tensile test (indirect tension), which is described in detail by Hadley, Hudson, and Kennedy (15). The splitting tensile test was conducted at 68°F (20°C) with a loading rate of 2-inches per minute. Stress, strain and modulus of elasticity were computed for each specimen at the point of failure using a value of 0.35 for Poisson's ratio. A summary of the test results for the Hveem specimens containing gravel and limestone is given in Tables B4 and B5, respectively. (Each value in the figures and tables represents an average of three tests.)

Optimum Asphalt Content

The optimum asphalt cement content was selected for both types of aggregate to be used in all mixtures for further testing and evaluation of shale oil asphalts. The selection was based primarily on the results of the test series conducted on the Marshall specimens using the mixture design selection procedures described by the Asphalt Institute (14). However, the results of the test series conducted on the Hveem specimens and engineering judgement also entered into the final selection. The properties of the mixtures using rounded gravel and crushed limestone at optimum asphalt content are given in Table B6.

It should be noted that some of the properties of the compacted mixtures at optimum asphalt content did not meet the criteria established by the Asphalt Institute (14). For example, considering the rounded gravel mixtures, the average values for Marshall flow, air void content, VMA and Hveem stability were less than those specified. Considering the crushed limestone mixtures, the average values for air void content and VMA were also less than specified. The action of traffic on an asphalt concrete pavement with qualities such as those mentioned above is likely to display plastic instability or, possibly flushing after a period of time. Undoubtedly, the quality of these mixtures could have been improved by adjusting the aggregate gradation and/or the asphalt content. However, since these mixtures were to be used as laboratory standards for test comparisons and not highway paving, no attempt was made to further adjust the mixture design.

Table B4. Data Summary of Hveem Specimens Using Rounded Gravel.

Asphalt Content, Percent by wt. Dry Aggregate	2.5	3.0	3.5	4.0	4.5
Bulk Specific Gravity of Compacted Mix	2.34	2.39	2.40	2.43	2.45
Maximum Specific Gravity of Mixture	2.53	2.52	2.50	2.48	2.46
Effective Specific Gravity of Aggregate	2.63	2.64	2.63	2.63	2.63
Asphalt Absorption, Percent by wt. Aggregate	0.72	0.83	0.81	0.77	0.71
Effective Asphalt Content, Percent by wt. Total Mix	1.7	2.1	2.6	3.1	3.6
Voids in Mineral Aggregate, Percent Bulk Volume	11.7	10.0	10.0	9.6	9.3
VMA Filled with Asphalt, Percent VMA	42	58	68	81	95
Air Void Content, Percent Total Volume	7.7	5.0	3.8	2.2	0.6
Resilient Modulus (M_R), 68°F (20°C), psi	407,000	515,000	513,000	562,000	477,000
Hveem Stability, percent	33	30	27	22	21
Splitting Tensile Stress @ Failure, 68°F (20°C), psi	92	103	121	114	119
Splitting Tenisle Strain @ Failure, 68°F (20°C), in/in	0.0025	0.0027	0.0027	0.0032	0.0037
Splitting Tensile Modulus (E) @ Failure, 69°F (20°C), psi	36,500	38,400	44,100	36,100	33,100

Table B5. Data Summary of Hveem Specimens Using Crushed Limestone.

Asphalt Content, Percent by Wt. Aggregate	3.5	4.0	4.5	5.0	5.5	6.0
Bulk Specific Gravity of Compacted Mix	2.44	2.45	2.46	2.44	2.47	2.47
Maximum Specific Gravity of Mixture	2.55	2.53	2.53	2.50	2.49	2.48
Effective Specific Gravity of Aggregate	2.70	2.69	2.71	2.69	2.70	2.71
Asphalt Absorption, Percent by Wt. Aggregate	1.6	1.5	1.8	1.5	1.6	1.8
Effective Asphalt Content, Percent by Wt. Total Mix	1.8	2.4	2.6	3.4	3.7	4.0
Voids in Mineral Aggregate, Percent Bulk Volume	9.0	9.0	9.1	10.3	9.6	10.0
VMA Filled with Asphalt, Percent VMA	64	74	81	84	94	97
Air Void Content, Percent Total Volume	4.5	3.2	2.5	2.2	0.8	0.4
Resilient Modulus (M_R), psi	618,000	620,000	590,000	499,000	571,000	249,000
Hveem Stability, Percent	57	54	54	50	46	24
Splitting Tensile Stress @ Failure 68°F (20°C), psi	119	112	112	106	105	82
Splitting Tensile Strain @ Failure 68°F (20°C), in/in	.0032	.0032	.0044	.0041	.0035	.0069
Splitting Tensile Modulus (E) @ Failure, 68°F (20°C), psi	37,200	34,800	26,000	27,400	30,000	12,000

Table B6. Mixture Properties with Laboratory Standard Asphalt at Optimum Asphalt Content.

Property	Rounded Gravel	Crushed Limestone
Design Asphalt Content, Percent by wt. Aggregate	3.8	4.5
Marshall Specimens		
Unit Weight, pcf	152	153
Air Void Content, Percent	2.1	3.0
VMA, Percent	9.1	10.5
VMA Filled with Asphalt, Percent	80	78
Marshall Stability, lbs	1270	2740
Marshall Flow, .01 inch	7	11
Hveem Specimens		
Unit Weight, pcf	151	154
Air Void Content, Percent	2.9	2.5
VMA, Percent	9.7	9.1
VMA Filled with Asphalt, Percent	76	81
Hveem Stability, Percent	25	54
Resilient Modulus, psi	570,000	590,000
Elastic Modulus, @ Failure *	39,000	26,000

*From Splitting Tensile Test

APPENDIX C

Resilient Modulus of Individual Specimens

Table C1. Resilient Modulus of Gyratory Compacted Specimens with Gravel at 68°F (20°C).

Asphalt D		Asphalt F		Asphalt R		Asphalt LS	
Sample Number	Resilient Modulus, psi x 10^6	Sample Number	Resilient Modulus, psi x 10^6	Sample Number	Resilient Modulus, psi x 10^6	Sample Number	Resilient Modulus, psi x 10^6
D-1	0.34	F-1	0.34	R-1	0.62	LS-1	0.48
D-2	0.32	F-2	0.39	R-2	0.66	LS-2	0.51
D-3	0.32	F-3	0.38	R-3	0.82	LS-3	0.51
D-4	0.33	F-4	0.27	R-4	0.67	LS-4	0.48
D-5	0.37	F-5	0.27	R-5	0.77	LS-5	0.52
D-6	0.35	F-6	0.31	R-6	0.78	LS-6	0.41
D-7	0.28	F-7	0.32	R-7	0.84	LS-7	0.53
D-8	0.37	F-8	0.24	R-8	0.61	LS-8	0.54
D-9	0.42	F-9	0.35	R-9	0.53	LS-9	0.51
D-10	0.39	F-10	0.28	R-10	0.83	LS-10	0.66
D-11	0.39	F-11	0.36	R-11	0.45	LS-11	0.47
D-12	0.35	F-12	0.35	R-12	0.66	LS-12	0.56
D-13	0.39	F-13	0.31	R-13	0.87		
D-14	0.25	F-14	0.32	R-14	0.47		
D-15	0.34	F-15	0.25	R-15	0.71		
D-16	0.33	F-16	0.31	R-16	0.55		
D-17	0.24	F-17	0.34	R-17	0.52		
D-18	0.25	F-18	0.32	R-18	0.71		
D-19	0.27	F-19	0.31	R-19	0.55		
D-20	0.33	F-20	0.34	R-20	0.88		
D-21	0.25	F-21	0.32	R-21	0.52		
D-22	0.33	F-22	0.28	R-22	0.55		
D-23	0.32	F-23	0.31	R-23	0.51		
D-24	0.21	F-24	0.36	R-24	0.63		
D-25	0.38	F-25	0.25	R-25	0.52		
D-26	0.23	F-26	0.30	R-26	0.60		
D-27	0.34	F-27	0.35	R-27	0.49		
D-28	0.41	F-28	0.32	R-28	0.72		
D-29	0.35	F-29	0.35	R-29	0.70		
D-30	0.28	F-30	0.27	R-30	0.65		
D-31	0.32	F-31	0.29	R-31	0.36		
D-32	0.45	F-32	0.33	R-32	0.53		
D-33	0.53	F-33	0.39	R-33	0.59		

English to Metric Conversion: 1 psi = 6.895 x 10^3 pascals

Table C2. Resilient Modulus of Gyratory Compacted Specimens with Limestone at 68°F (20°C).

Asphalt D		Asphalt F		Asphalt R		Asphalt LS	
Sample Number	Resilient Modulus, psi x 10^6	Sample Number	Resilient Modulus, psi x 10^6	Sample Number	Resilient Modulus, psi x 10^6	Sample Number	Resilient Modulus, psi x 10^6
D-1	0.52	F-1	0.49	R-1	0.69	LS-1	0.63
D-2	0.47	F-2	0.55	R-2	0.60	LS-2	0.78
D-3	0.51	F-3	0.52	R-3	0.62	LS-3	0.71
D-4	0.55	F-4	0.56	R-4	0.61	LS-4	0.67
D-5	0.47	F-5	0.46	R-5	0.59	LS-5	0.77
D-6	0.58	F-6	0.44	R-6	0.75	LS-6	0.75
D-7	0.61	F-7	0.53	R-7	0.77	LS-7	0.67
D-8	0.49	F-8	0.39	R-8	0.79	LS-8	0.80
D-9	0.55	F-9	0.57	R-9	0.81	LS-9	0.56
D-10	0.48	F-10	0.41	R-10	0.64	LS-10	0.77
D-11	0.52	F-11	0.45	R-11	0.63	LS-11	0.83
D-12	0.44	F-12	0.47	R-12	0.54	LS-12	0.66
D-13	0.54	F-13	0.49	R-13	0.78		
D-14	0.53	F-14	0.50	R-14	0.69		
D-15	0.53	F-15	0.49	R-15	0.77		
D-16	0.52	F-16	0.45	R-16	0.95		
D-17	0.56	F-17	0.58	R-17	0.72		
D-18	0.55	F-18	0.48	R-18	1.00		
D-19	0.54	F-19	0.55	R-19	0.86		
D-20	0.45	F-20	0.40	R-20	0.82		
D-21	0.52	F-21	0.45	R-21	0.60		
D-22	0.46	F-22	0.43	R-22	0.63		
D-23	0.44	F-23	0.37	R-23	0.68		
D-24	0.42	F-24	0.48	R-24	0.79		
D-25	0.44	F-25	0.38	R-25	0.87		
D-26	0.43	F-26	0.47	R-26	0.66		
D-27	0.51	F-27	0.46	R-27	0.85		
D-28	0.36	F-28	0.50	R-28	0.81		
D-29	0.42	F-29	0.55	R-29	0.77		
D-30	0.49	F-30	0.45	R-30	0.80		
D-31	0.48	F-31	0.54	R-31	0.58		
D-32	0.43	F-32	0.47	R-32	0.62		
D-33	0.46	F-33	0.53	R-33	0.90		

English to Metric Conversion: 1 psi = 61895 x 10^3 pascals

Table C3. Resilient Modulus of Specimens Made with Gravel.

		Resilient Modulus in psi x 10^6 at					
Asphalt	Sample No.	-13°F	33°F	68°F	77°F	104°F	68°F After Soaking
D	D1	6.09	3.35	0.338	0.132	0.044	0.205
	D2	7.29	3.64	0.321	0.149	0.046	0.120
	D3	7.60	3.37	0.325	0.179	0.054	0.224
	Average	6.99	3.45	0.328	0.153	0.048	0.183
F	F1	7.17	3.08	0.336	0.155	0.051	0.219
	F2	6.88	2.71	0.394	0.152	0.053	0.248
	F3	6.82	2.31	0.374	0.166	0.054	0.226
	Average	7.14	2.70	0.368	0.157	0.053	0.231
R	R1	6.69	3.17	0.622	0.265	0.057	0.502
	R2	6.53	3.36	0.663	0.362	0.072	0.603
	R3	6.57	3.15	0.817	0.392	0.077	0.729
	Average	6.60	3.23	0.701	0.340	0.068	0.611

1 psi = 6.895 kPa

Table C4. Resilient Modulus of Specimens Made with Limestone.

Asphalt	Sample No.	Resilient Modulus in psi x 10^6 at -13°F	33°F	68°F	77°F	104°F	68°F After Soaking
D	D1	5.458	2.631	0.520	0.268	0.090	0.414
	D2	5.487	2.880	0.467	0.318	0.094	0.469
	D3	5.381	2.888	0.506	0.315	0.109	0.471
	Average	5.442	2.800	0.498	0.300	0.098	0.451
F	F1	5.724	2.671	0.495	0.273	0.087	0.282
	F2	5.670	2.558	0.550	0.300	0.091	0.287
	F3	5.618	2.446	0.523	0.280	0.090	0.279
	Average	5.671	2.565	0.523	0.284	0.090	0.279
R	R1	5.381	3.036	0.687	0.366	0.075	0.631
	R2	5.587	2.558	0.595	0.308	0.065	0.571
	R3	5.474	2.530	0.620	0.318	0.066	0.527
	Average	5.481	2.708	0.634	0.331	0.069	0.576

1 psi = 6.895 kPa

APPENDIX D

Splitting Tensile Test Data for Individual Specimens

Table D1. Splitting Tensile Test Data for Asphalt D with Gravel.

Displacement Rate, in/min (cm/min)	Temperature °F(°C)	Sample Number	Stress* psi	Strain* in/in	Modulus* psi
2.0 (5.1)	68°(20°)	D-22	76	0.0025	31,000
		D-24	63	0.0037	17,000
		D-23	72	0.0032	22,000
	33°(1°)	D-13	413	0.0018	233,000
		D-14	379	0.0016	237,000
		D-15	426	0.0013	319,000
	-13°(-25°)	D-4	414	0.0009	466,000
		D-5	453	0.0004	1,275,000
		D-6	304	0.0001	4,313,000
0.20 (0.51)	68°(20°)	D-25	32	0.0024	13,000
		D-26	25	0.0044	6,000
		D-27	32	0.0022	14,000
	33°(1°)	D-16	187	0.0025	75,000
		D-17	143	0.0027	54,000
		D-18	206	0.0027	76,000
	-13°(-25°)	D-7	414	0.0001	3,325,000
		D-8	448	0.0001	6,298,000
		D-9	458	0.0003	1,369,000
0.02 (0.051)	68°(20°)	D-28	16	0.0030	5,000
		D-30	10	0.0035	3,000
		D-29	15	0.0033	5,000
	33°(1°)	D-19	69	0.0034	20,000
		D-20	65	0.0014	46,000
		D-21	46	0.0016	28,000
	-13°(-25°)	D-10	301	--	--
		D-11	259	--	--
		D-12	416	0.0002	17,000

*All Values Measured at the Point of Failure.

English to Metric Conversion: 1 psi = 6.895×10^3 Pascals.

Table D2. Splitting Tensile Test Data for Asphalt F with Gravel.

Displacement Rate, in/min (cm/min)	Temperature °F(°C)	Sample Number	Stress* psi	Strain* in/in	Modulus* psi
2.0 (5.1)	68°(20°)	F-22	75	0.0026	29,000
		F-24	72	0.0030	24,000
		F-23	73	0.0061	12,000
	33°(1°)	F-13	439	0.0020	225,000
		F-14	432	0.0014	304,000
		F-15	423	0.0012	367,000
	-13°(-25°)	F-4	339	0.0001	6,357,000
		F-5	442	0.0001	6,214,000
		F-6	232	--	--
0.2 (0.51)	68°(20°)	F-25	27	0.0036	8,000
		F-26	23	0.0028	8,000
		F-27	36	0.0026	14,000
	33°(1°)	F-16	179	0.0019	96,000
		F-17	182	0.0012	152,000
		F-18	206	0.0018	116,000
	-13°(-25°)	F-7	513	0.0001	3,725,000
		F-8	480	--	--
		F-9	--	--	--
0.02 (0.051)	68°(20°)	F-29	14	0.0035	4,000
		F-28	16	0.0032	5,000
		F-30	26	0.0035	8,000
	33°(1°)	F-19	58	0.0018	32,000
		F-20	54	0.0019	29,000
		F-21	52	0.0021	25,000
	-13°(-25°)	F-10	445	0.0004	1,056,000
		F-11	461	0.0004	1,120,000
		F-12	426	0.0001	4,941,000

*All Values Measured at the Point of Failure.

English to Metric Conversion: 1 psi = 6.895 x 10^3 Pascals.

Table D3. Splitting Tensile Test Data for Asphalt R with Gravel.

Displacement Rate, in/min (cm/min)	Temperature °F(°C)	Sample Number	Stress* psi	Strain* in/in	Modulus* psi
2.0 (5.1)	68°(20°)	R-22	125	0.0027	47,000
		R-24	135	0.0032	42,000
		R-23	113	0.0023	49,000
	33°(1°)	R-13	505	0.0004	1,136,000
		R-14	443	0.0012	370,000
		R-15	515	0.0021	241,000
	-13°(-25°)	R-4	557	0.0001	7,837,000
		R-5	462	--	--
		R-6	426	0.0003	1,303,000
0.2 (0.51)	68°(20°)	R-25	52	0.0043	12,000
		R-26	52	0.0028	18,000
		R-27	49	0.0027	18,000
	33°(1°)	R-16	275	0.0014	193,000
		R-17	281	0.0018	158,000
		R-18	320	0.0014	225,000
	-13°(-25°)	R-7	445	0.0001	3,577.000
		R-9	583	0.0001	5,855,000
		R-8	--	--	--
0.02 (0.051)	68°(20°)	R-28	26	0.0035	8,000
		R-30	21	0.0036	6,000
		R-29	23	0.0028	8,000
	33°(1°)	R-19	99	0.0020	50,000
		R-20	124	0.0016	79,000
		R-21	87	0.0018	49,000
	-13°(-25°)	R-10	453	0.0003	1,578,000
		R-11	449	0.0003	1,511,000
		R-12	447	0.0003	1,555,000

*All Values Measured at the Point of Failure.

English to Metric Conversion: 1 psi = 6.895 x 10^3 Pascals.

Table D4. Splitting Tensile Test Data for Asphalt D with Limestone.

Displacement Rate, in/min (cm/min)	Temperature °F(°C)	Sample Number	Stress* psi	Strain* in/in	Modulus* psi
2.0 (5.1)	68°(20°)	D-22	78	0.0073	11,000
		D-24	89	0.0038	24,000
		D-23	90	0.0024	38,000
	33°(1°)	D-13	499	0.0011	468,000
		D-14	466	0.0016	291,000
		D-15	593	0.0014	417,000
	-13°(-25°)	D-4	--	--	--
		D-5	769	0.0004	1,785,000
		D-6	686	0.0005	1,369,000
0.20 (0.51)	68°(20°)	D-27	43	0.0025	17,000
		D-26	41	0.0028	14,000
		D-25	41	0.0035	12,000
	33° (1°)	D-16	260	0.0012	208,000
		D-17	268	0.0012	216,000
		D-18	276	0.0013	216,000
	-13°(-25°)	D-7	592	0.0002	3,533,000
		D-8	621	0.0002	3,814,000
		D-9	504	0.0001	4,390,000
0.02 (0.051)	68°(20°)	D-30	24	0.0027	9,000
		D-29	22	0.0053	4,000
		D-28	21	0.0043	5,000
	33°(1°)	D-19	84	0.0026	32,000
		D-20	86	0.0022	39,000
		D-21	106	0.0019	56,000
	-13°(-25°)	D-10	564	0.0003	1,758,000
		D-11	474	0.0004	1,355,000
		D-12	630	0.0005	1,328,000

*All Values Measured at the Point of Failure.

English to Metric Conversion: 1 psi = 6.895 x 10^3 Pascals.

Table D5. Splitting Tensile Test Data for Asphalt F with Limestone.

Displacement Rate, in/min (cm/min)	Temperature °F(°C)	Sample Number	Stress* psi	Strain* in/in	Modulus* psi
2.0 (5.1)	68°(20°)	F-22	81	0.0021	38,000
		F-24	102	0.0021	48,000
		F-23	80	0.0027	30,000
	33°(1°)	F-13	378	0.0036	104,000
		F-14	451	0.0009	507,000
		F-15	427	0.0012	343,000
	-13°(-25°)	F-4	847	0.0001	6,432.000
		F-5	845	0.0001	6,087,000
		F-6	888	0.0017	5,148,000
0.20 (0.51)	68°(20°)	F-27	37	0.0037	10,000
		F-26	39	0.0028	14,000
		F-25	31	0.0020	16,000
	33°(1°)	F-16	219	0.0016	137,000
		F-17	249	0.0018	135,000
		F-18	228	0.0018	128,000
	-13°(-25°)	F-7	604	0.0002	3,320,000
		F-8	638	0.0002	3,027,000
		F-9	471	0.0001	4,919,000
0.02 (0.051)	68°(20°)	F-28	22	0.0039	6,000
		F-29	24	0.0038	6,000
		F-30	23	0.0046	5,000
	33°(1°)	F-19	--	--	--
		F-20	69	0.0012	57,000
		F-21	61	0.0013	48,000
	-13°(-25°)	F-10	510	0.0004	1,291,000
		F-11	492	0.0003	1,522,000
		F-12	524	0.0004	1,458,000

*All Values Measured at the Point of Failure.

English to Metric Conversion: 1 psi = 6.895 x 10^3 Pascals.

Table D6. Splitting Tensile Test Data for Asphalt R with Limestone.

Displacement Rate, in/min (cm/min)	Temperature °F(°C)	Sample Number	Stress* psi	Strain* in/in	Modulus* psi
2.0 (5.1)	68°(20°)	R-22	134	0.0023	58,000
		R-24	137	0.0024	57,000
		R-23	142	0.0028	50,000
	33°(1°)	R-13	544	0.0006	874,000
		R-14	531	0.0008	650,000
		R-15	469	0.0013	367,000
	-13°(-25°)	R-4	883	0.0002	5,121,000
		R-5	816	0.0002	4,735,000
		R-6	526	0.0001	5,497,000
0.20 (0.51)	68°(20°)	R-27	83	0.0018	47,000
		R-26	68	0.0035	20,000
		R-25	87	0.0030	29,000
	33°(1°)	R-16	396	0.0016	253,000
		R-17	372	0.0011	349,000
		R-18	349	0.0011	327,000
	-13°(-25°)	R-7	572	0.0005	3,730,000
		R-8	560	0.0001	3,899,000
		R-9	558	0.0002	2,913,000
0.02 (0.051)	68°(20°)	R-28	34	0.0038	9,000
		R-29	35	0.0041	9,000
		R-30	--	--	--
	33°(1°)	R-19	145	0.0012	120,000
		R-20	137	0.0015	92,000
		R-21	118	0.0019	61,000
	-13°(-25°)	R-10	567	0.0003	1,633,000
		R-11	577	0.0005	1,096,000
		R-12	545	0.0004	1,519,000

*All Values Measured at the Point of Failure.

English to Metric Conversion: 1 psi = 6.895×10^3 Pascals.

Table D7. Splitting Tensile Test Data For Water Saturated Samples.

Aggregate	Asphalt	Sample Number	Stress,* psi	Strain,* in/in	Modulus,* psi
Gravel	D	1	113	0.0053	21,000
		2	95	0.0069	14,000
		3	95	0.0054	18,000
	F	1	37	0.0073	12,000
		2	88	0.0044	20,000
		3	95	0.0060	16,000
	R	1	63	0.0034	19,000
		2	71	0.0028	25,000
		3	72	0.0027	27,000
Limestone	D	1	122	0.0034	36,000
		2	118	0.0034	35,000
		3	122	0.0036	34,000
	F	1	108	0.0036	31,000
		2	118	0.0041	29,000
		3	113	0.0050	23,000
	R	1	65	0.0028	23,000
		2	64	0.0043	15,000
		3	60	0.0037	16,000

*All tested at 68°F (20°C) at a rate of 2.0 in/min (5.08 cm/min). English to metric conversion: 1 psi = 6.895 x 10^3 pascals.

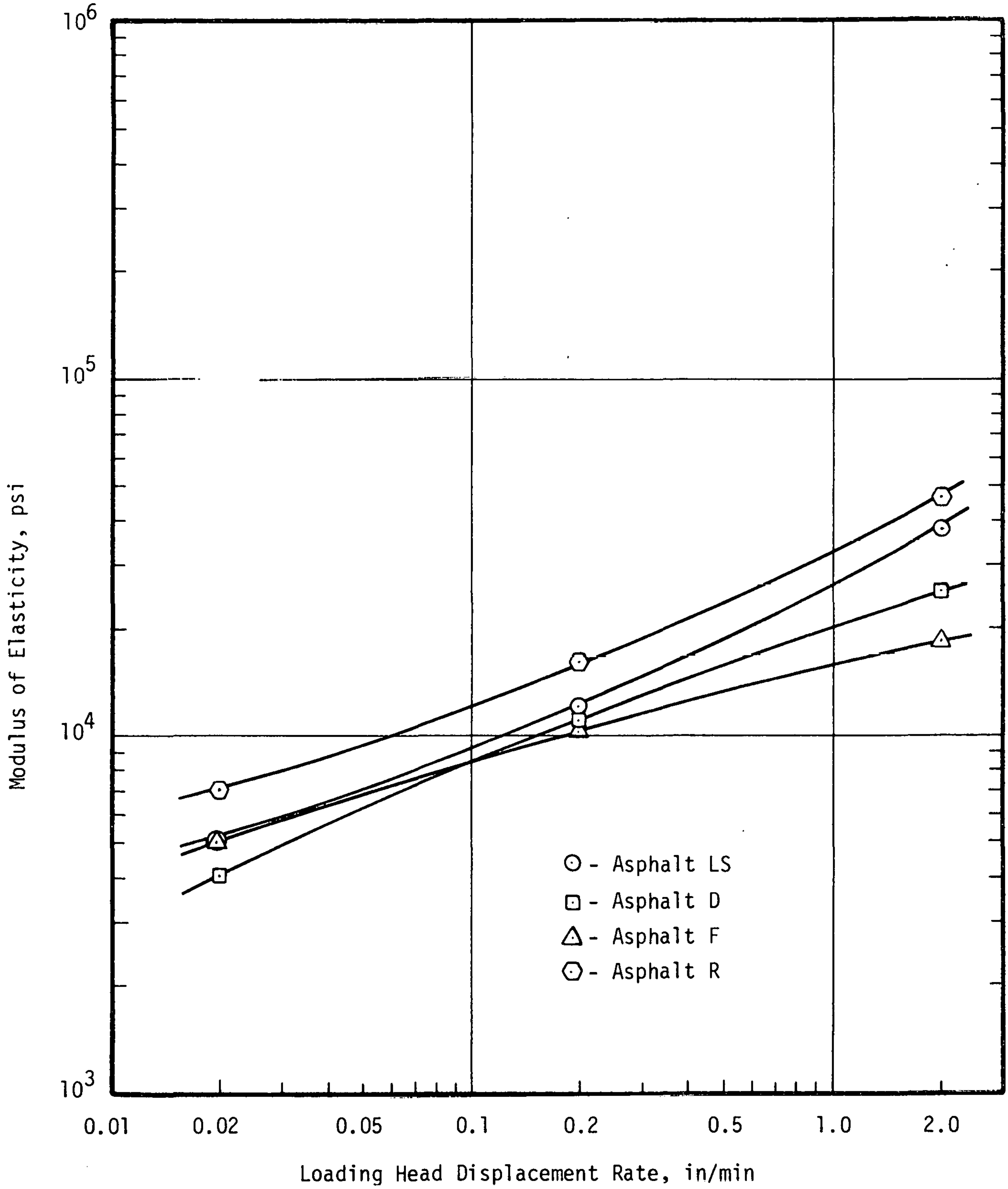

Figure D1. Secant Modulus versus Loading Rate for Gravel Specimens at 68°F (20°C)

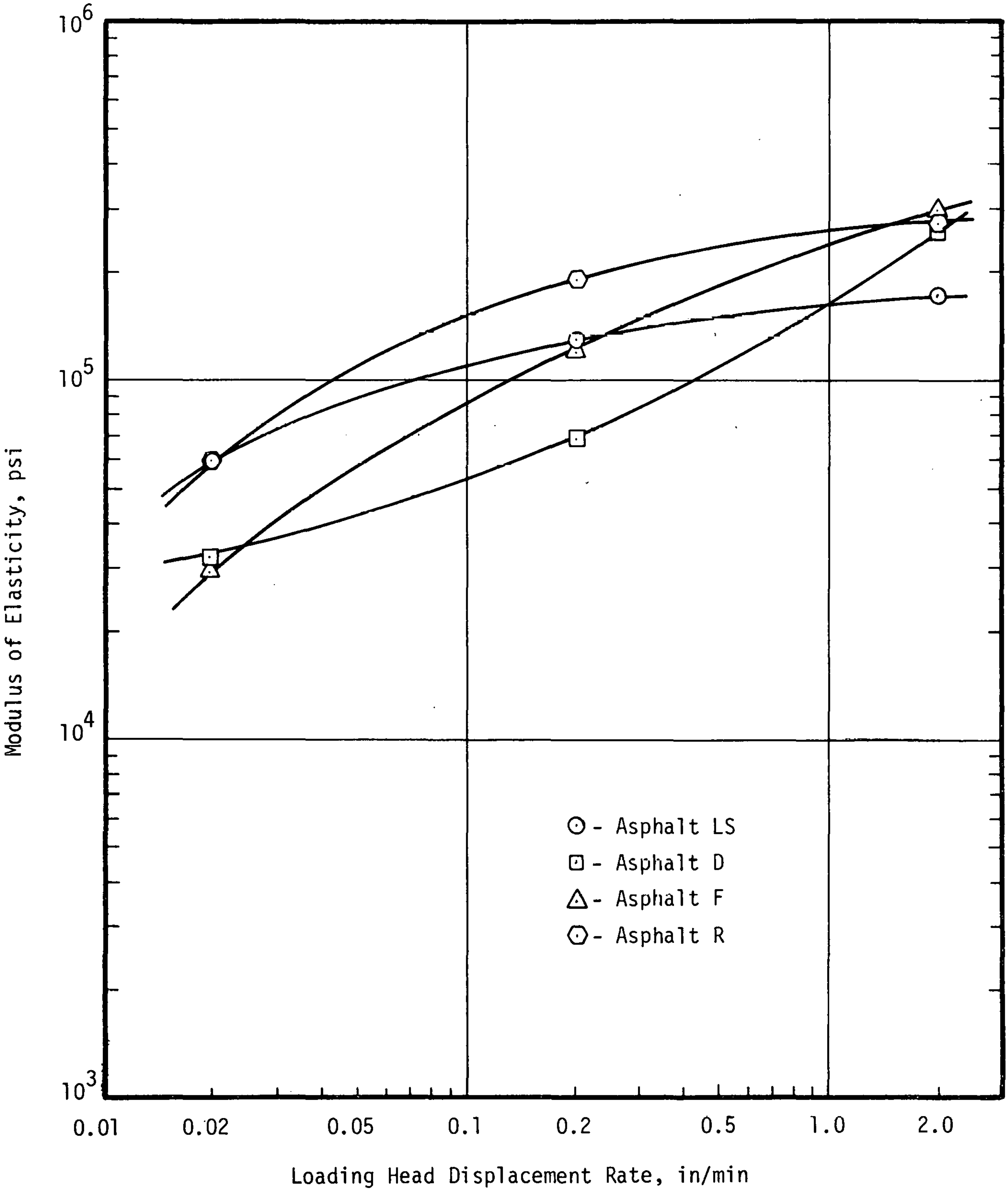

Figure D2. Secant Modulus versus Loading Rate for Gravel Specimens at 33°F (1°C)

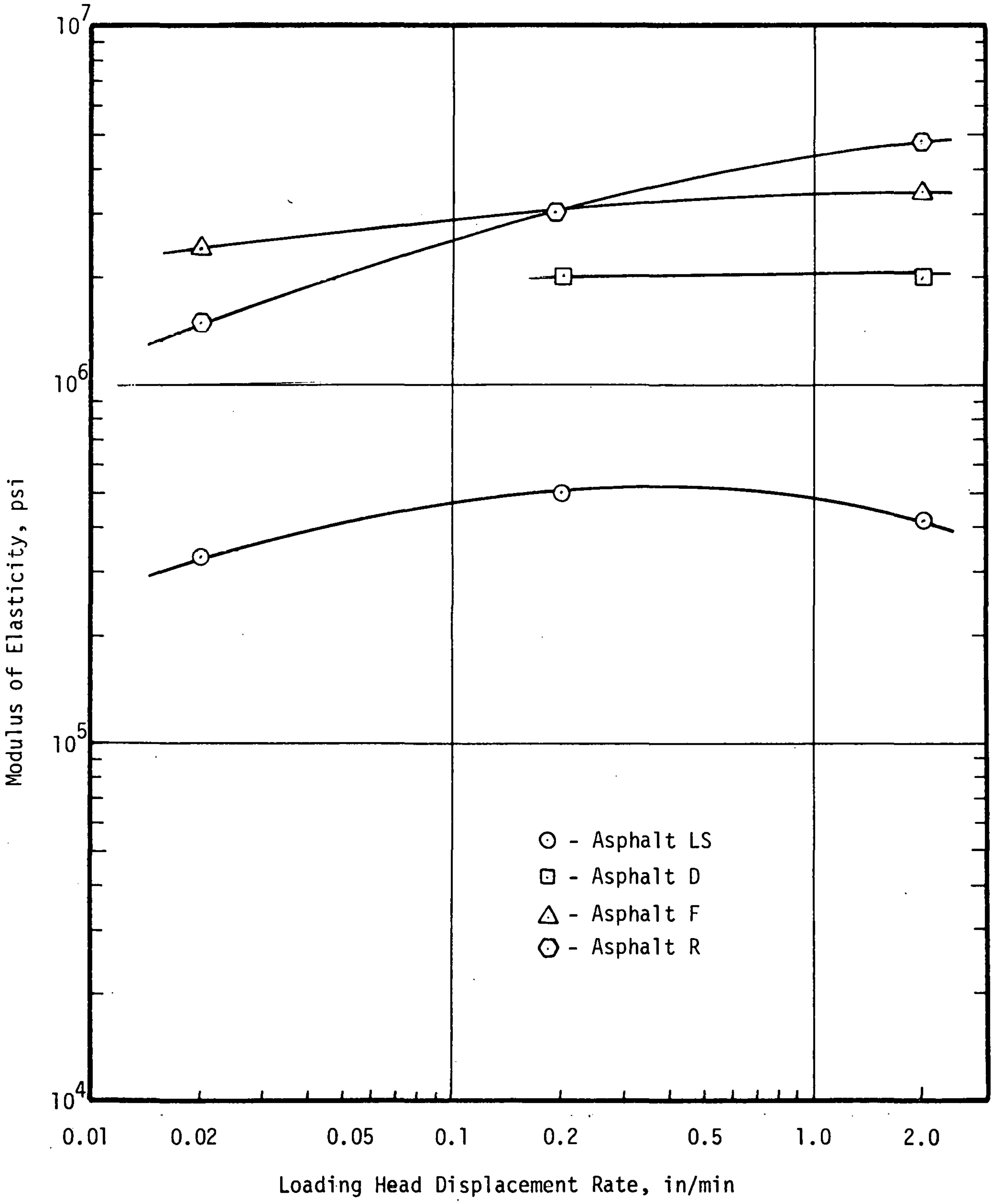

Figure D3. Secant Modulus versus Loading Rate for Gravel Specimens at -13°F(-25°C)

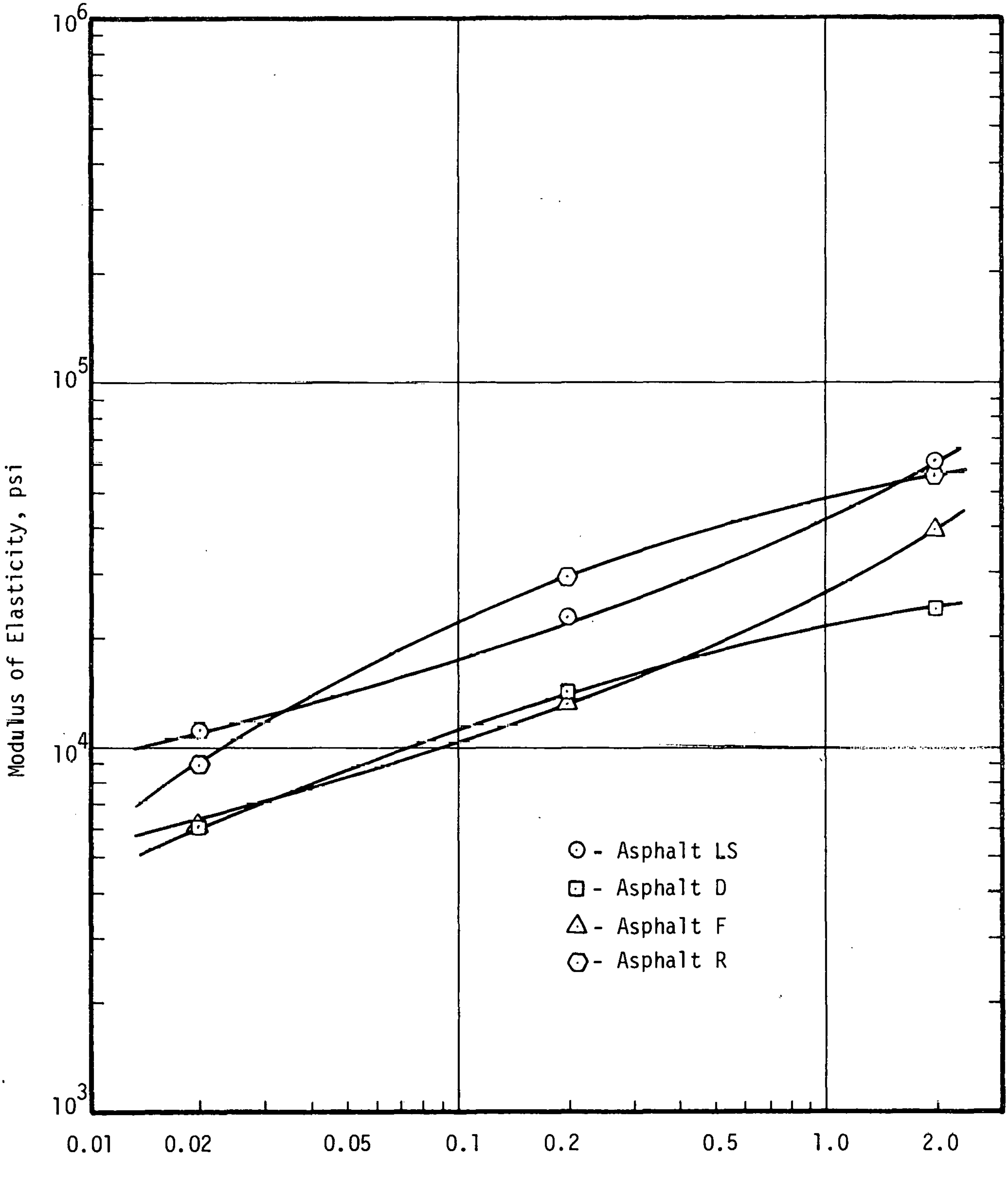

Figure D4. Secant Modulus versus Loading Rate for Limestone Specimens at 68°F (20°C)

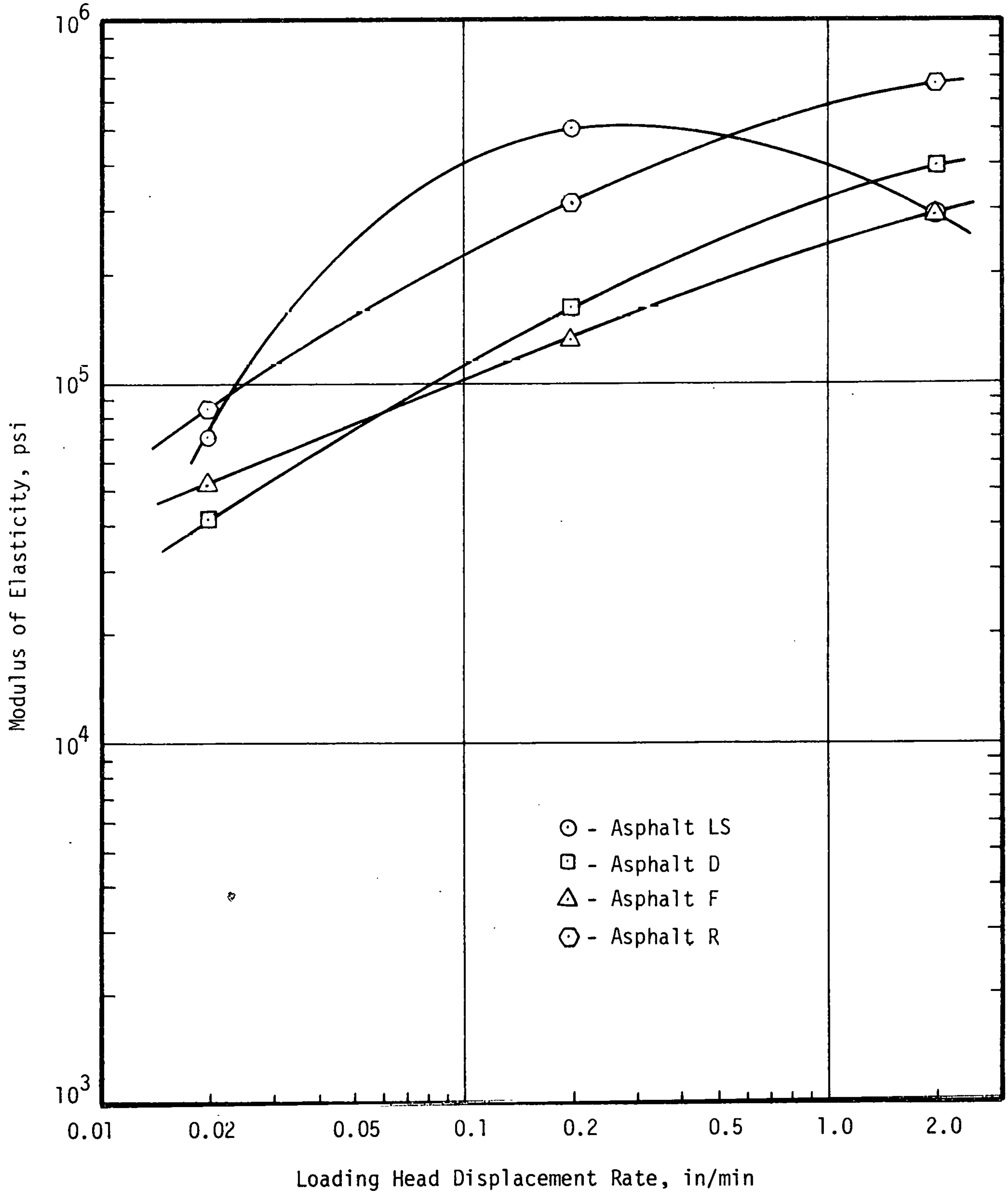

Figure D5. Secant Modulus versus Loading Rate for Limestone Specimens at 33°F (1°C)

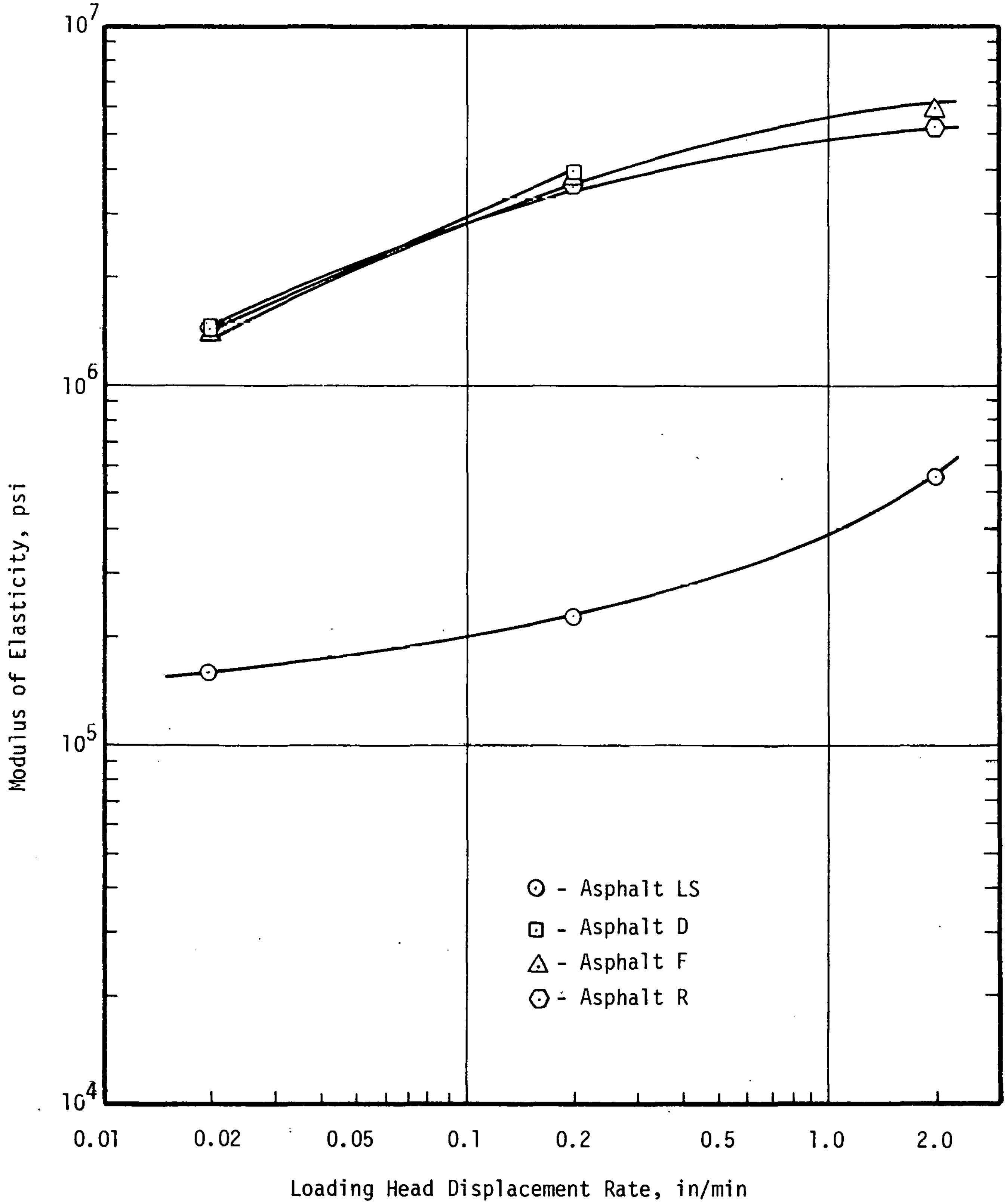

Figure D6. Secant Modulus versus Loading Rate for Limestone Specimens at -13°F (-25°C)

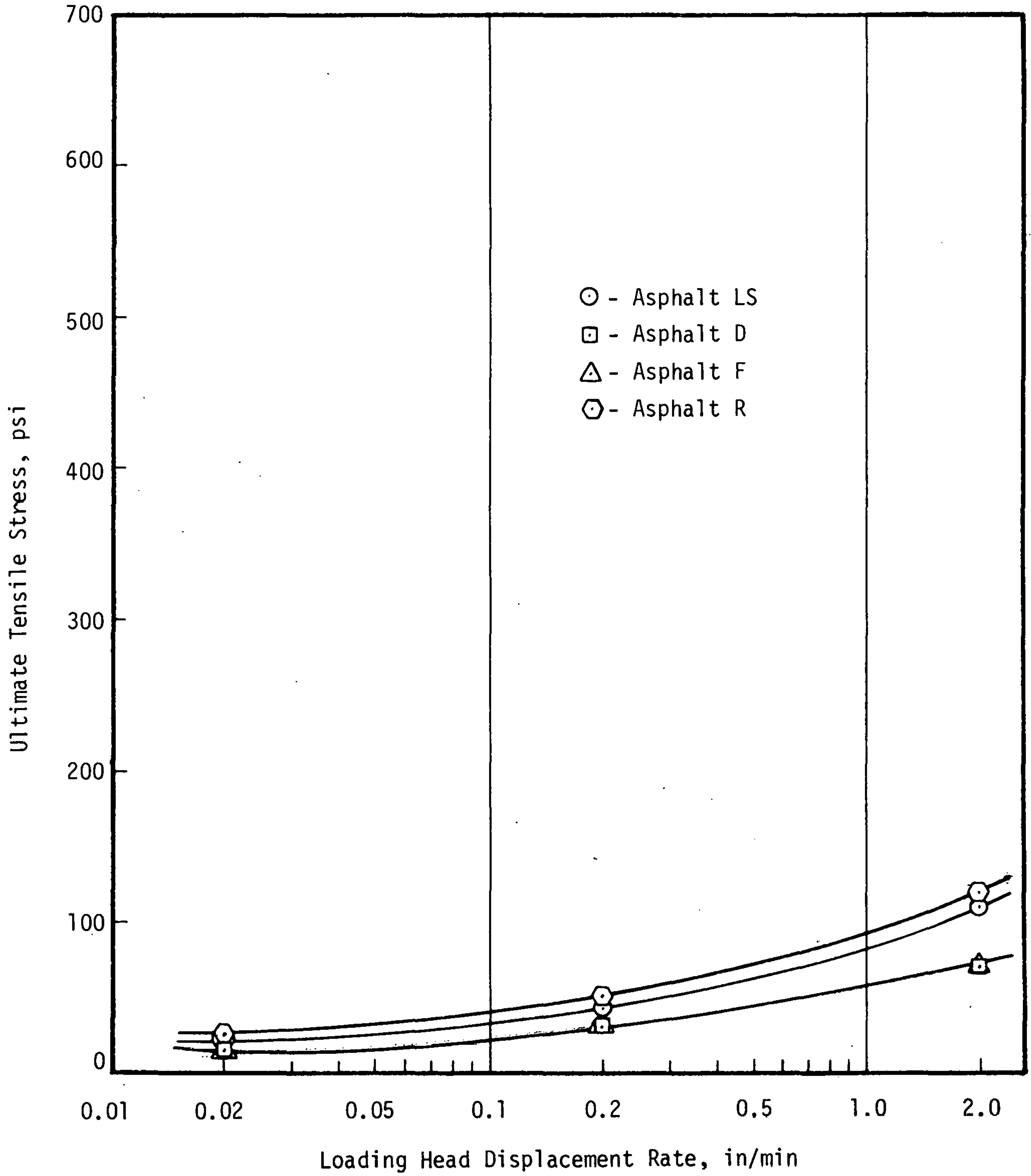

Figure D7. Tensile Strength versus Loading Rate for Gravel Specimens at 68°F (20°C)

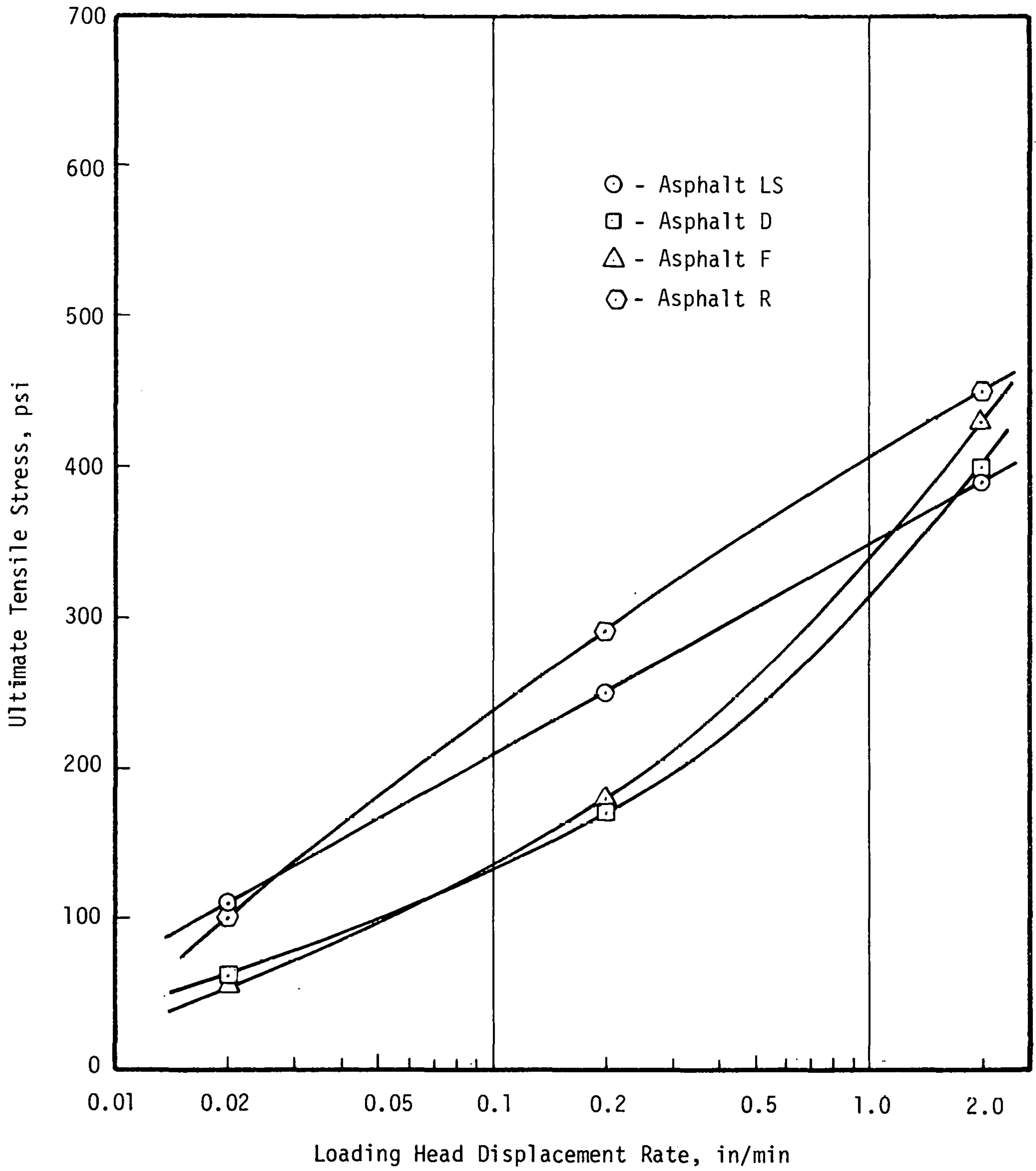

Figure D8. Tensile Strength versus Loading Rate for Gravel Specimens at 33°F (1°C)

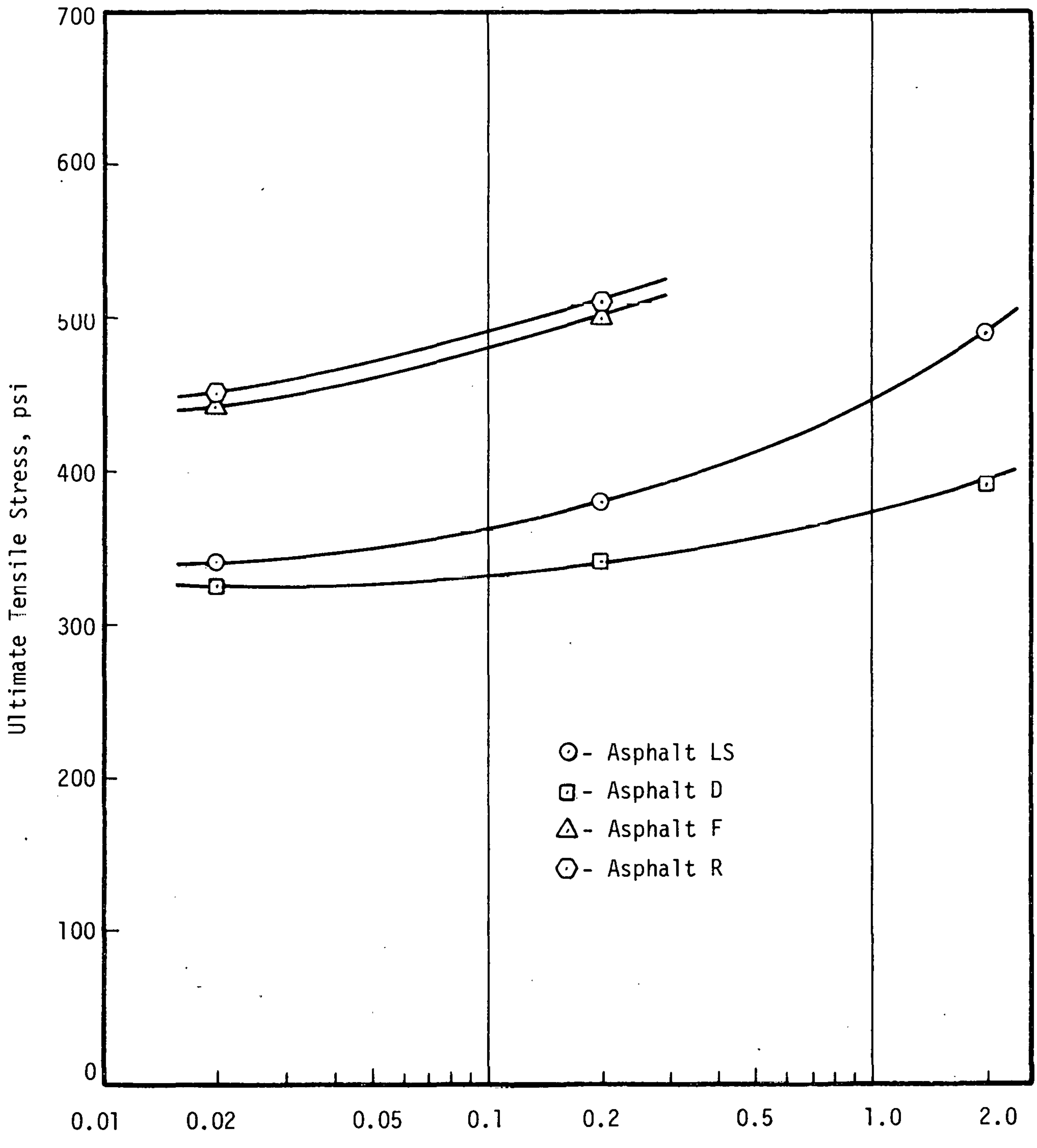

Figure D9. Tensile Strength versus Loading Rate for Gravel Specimens at -13°F (-25°C)

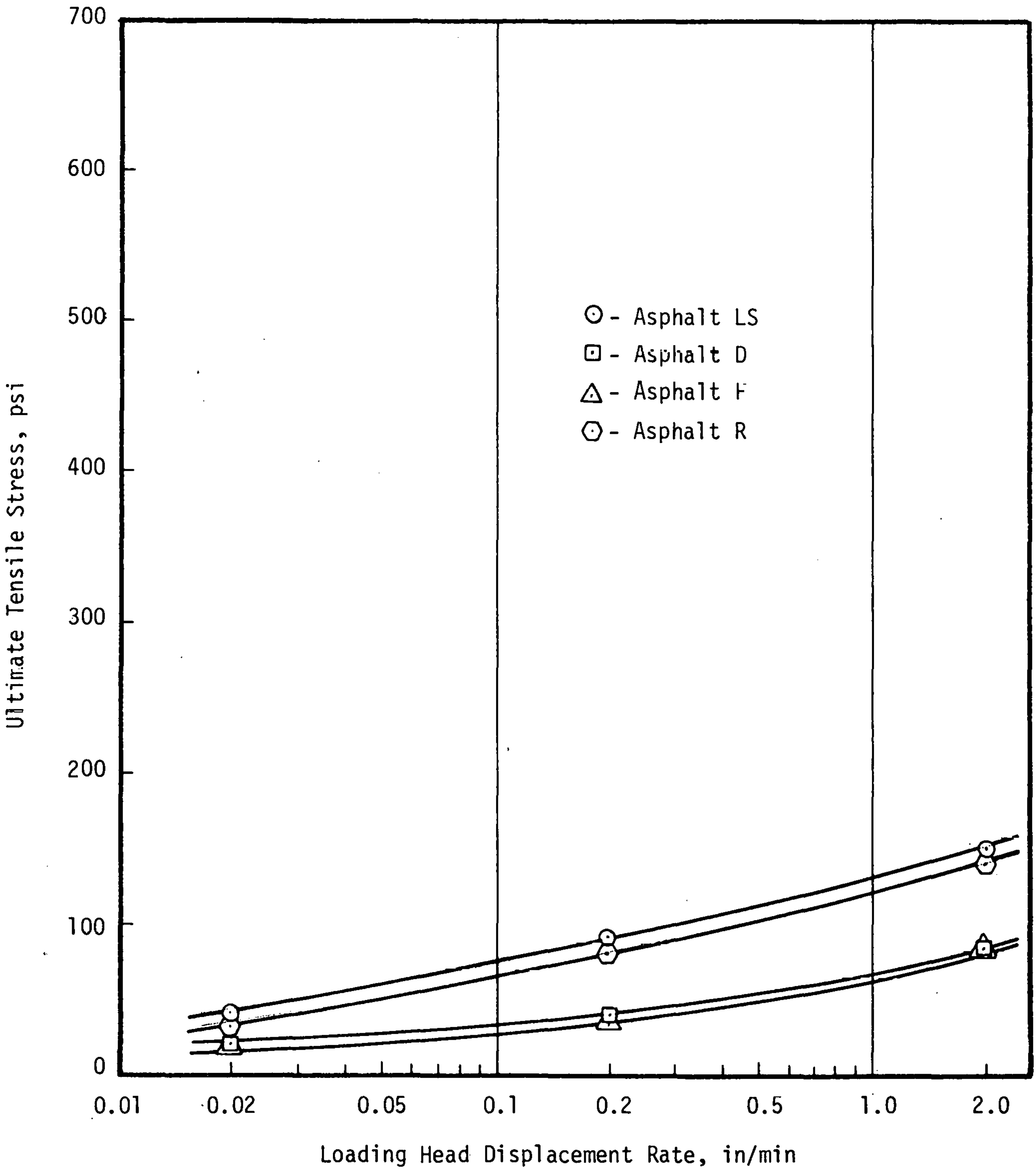

Figure D10. Tensile Strength versus Loading Rate for Limestone Specimens at 68°F (20°C)

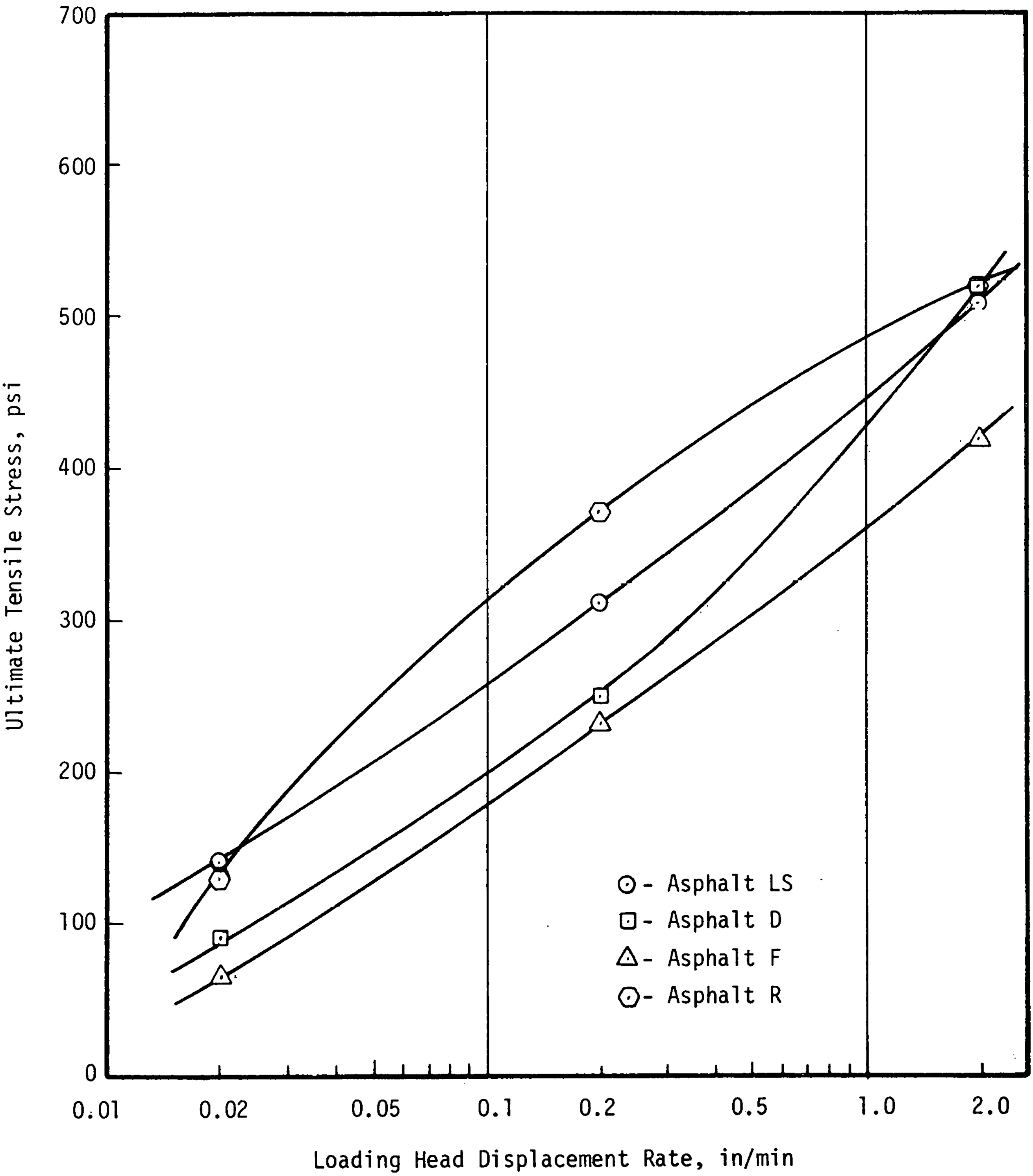

Figure D11. Tensile Strength versus Loading Rate for Limestone Specimens at 33°F (1°C)

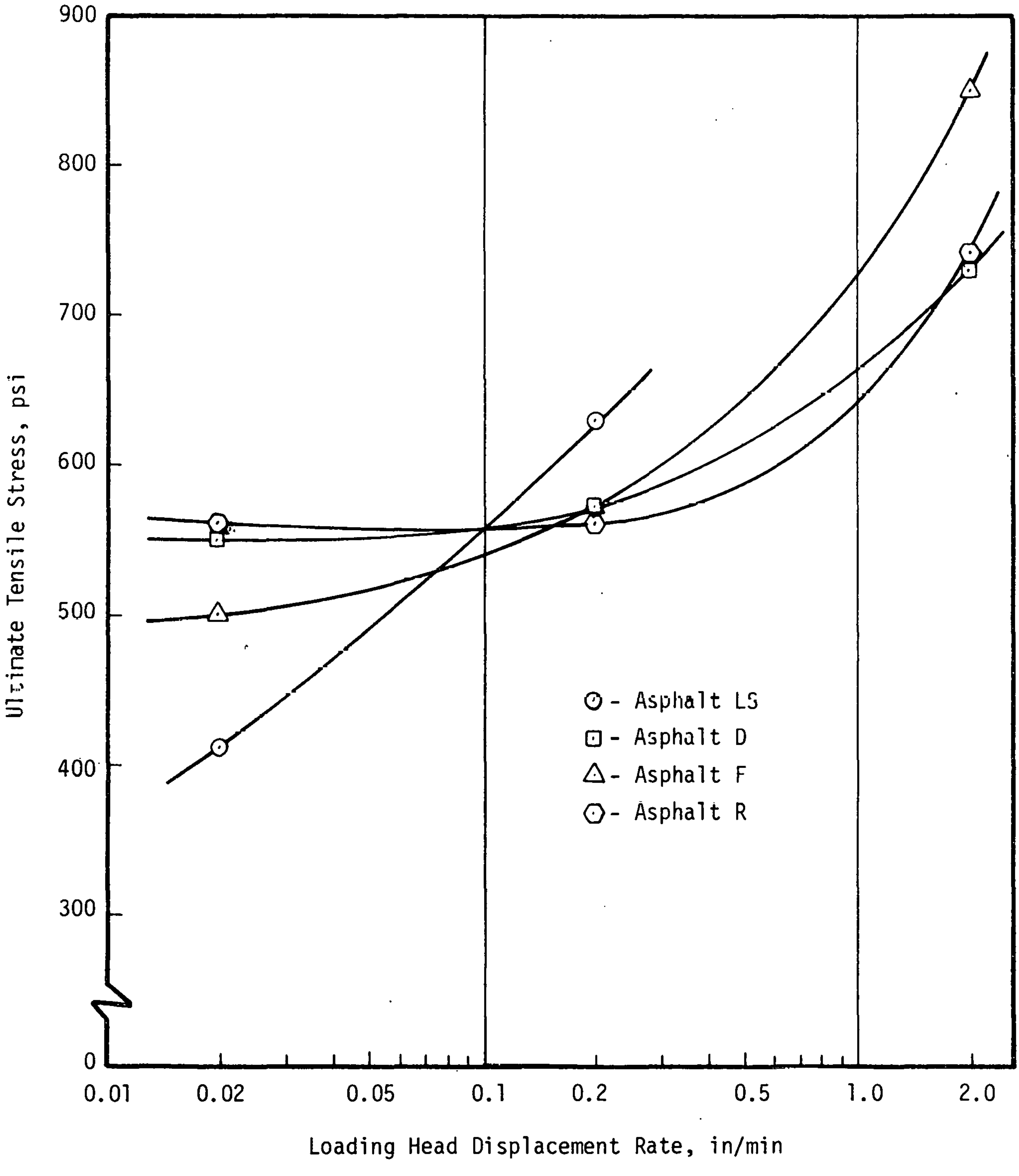

Figure D12. Tensile Strength versus Loading Rate for Limestone Specimens at -13°F (-25°C)

APPENDIX E

Locations of Major Tar Sand Deposits

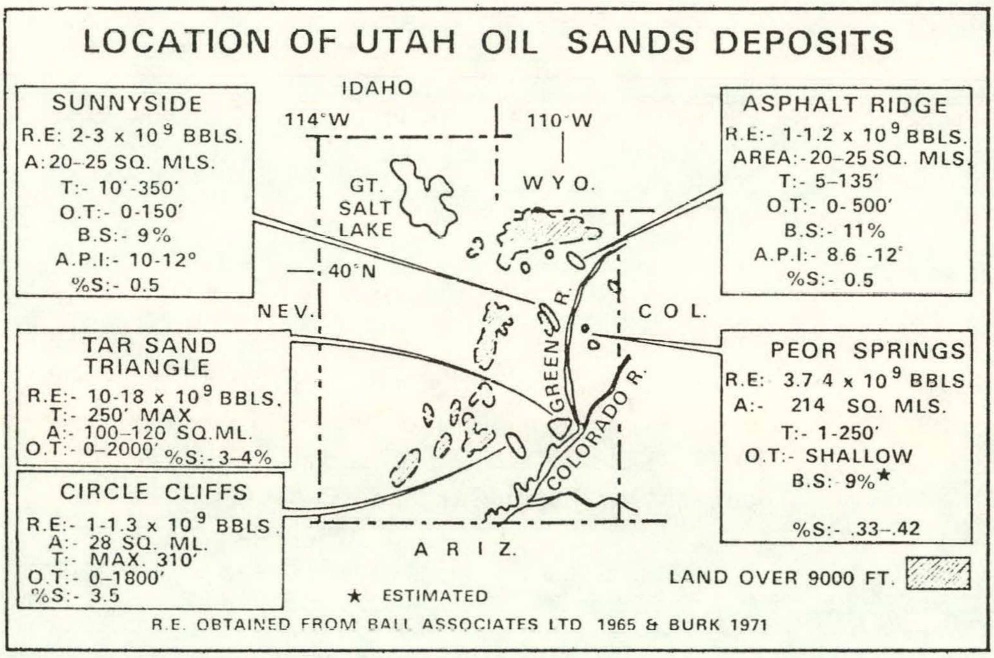

Figure E1. Location of Utah Oil Sand Deposits (5).

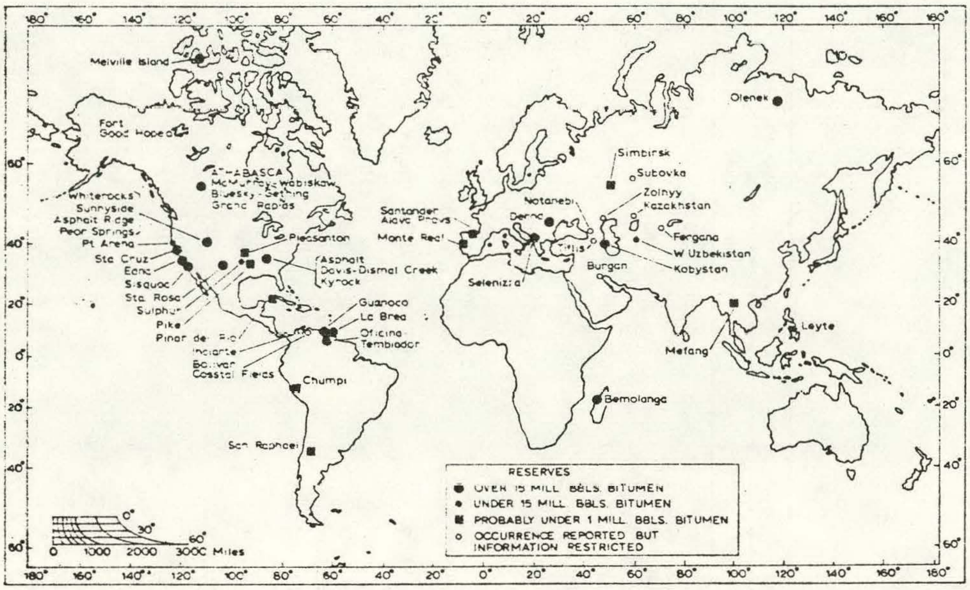

Figure E2. Location Map of Major Tar Sands of the World (16).

Table E1. Major Tar Sand Deposits of the World (16).

Country	Name of deposit	Age of reservoir rock	Areal extent acres	Pay thickness sq mi	ft	average	Bitumen sat. (wt%)	Character of oil °API at 60°F	(% sulfur)	Overburden thickness (ft)	In-place reserves (10^6 bbl)	No.
Canada	McMurray—Wabiskaw, Alberta		5,750,000	9000	0— 300	(175)	—	—	—	0—1900	625,900	
	Bluesky—Gething, Alberta		1,200,000	1875	0— 400		—	—	—	700—2600	51,500	
	Grand Rapids, Alberta		1,100,000	1625	400	(280)	—	—	—	300—1400	33,400	
	Total "Athabasca" tar sands	L. Cretaceous	8,000,000	12,500		(150*)	2—18	10.5	4.5		710,800	1
	Melville Island, N.W.T.	Triassic	?	?	60— 80		?—16	10	0.9—2.2	0—2000*	?	1a
Eastern Venezuela	Oficina—Temblador tar belt	Oligocene	5,750,000	9,000	3— 10			10		0—3000*	200,000	2
Malagasy	Bemolanga	Triassic	96,000	150	80— 300	(100)	10		0.7	0— 100	1750	3
U.S.A.	Asphalt Ridge, Utah	Oligocene and U. Cretaceous	11,000*		11— 254	(98)	11	8.6—12	0.5	0—2000	900	4
					24— 200	(100)						
	Sunnyside, Utah	U. Eocene	34,300*		10— 350		9	10 —12	0.5	0— 150	500	5
Albania	Selenizza	Mio-Pliocene	5306	8	33— 330	(50)*	8—14	4.6—13.2	6.1	shallow	371*	6
U.S.A.	Whiterocks, Utah	Jurassic	1900	3	900—1000		10	12	0.5	nil	250	7
	Edna, California	Mio-Pliocene	6595	10	0—1200*	(250)	9—16	13	4.2	0— 600*	165	8
	Peor Springs, Utah	U. Eocene	1735	3	1— 250	(34)*	9*			shallow	87	9
Eastern Venezuela	Guanoco	Recent (Alluvial)	1000	2	2— 9	(4)	64	8	5.9	nil	62	10
Trinidad	La Brea	U. Miocene	126		0— 270	(135)	54	1 — 2	6.0—8.0	nil	60	11
U.S.A.	Santa Rosa, New Mexico	Triassic	4630+	7	0— 100	(20)	4— 8			0— 40	57	12
	Sisquoc, California	U. Pliocene	175		0— 185	(85)	14—18	4 — 8		15— 70	50	13
	Asphalt, Kentucky	Pennsylvanian	7000	11	5— 36	(15)	8—10			6— 30	48	14
Rumania	Derna	Pliocene	459		6— 25		15—22		0.7	shallow	25	15
U.S.S.R.	Cheildag, Kazakhstan	M. Miocene	82*			(200)	5—13			shallow	24	16
U.S.A.	Davis—Dismal Creek, Kentucky	Pennsylvanian	1900	3	10— 50	(15)	5			15— 30	22	17
	Santa Cruz, California	Miocene	1200	2	5— 50	(11)	10—12			0— 100	20	18
	Kyrock, Kentucky	Pennsylvanian	900*	—	15— 40	(20)	6— 8			,15	18	19

* Statistics asterisked where estimated.

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